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STRUCTURAL AND STRATIGRAPHIC DATA OF NORTHEAST TEXAS PETROLEUM AREA.

F. JULIUS FOHS.*

INTRODUCTION.

To summarize the results of our five-year study of northeast Texas geology, to correlate it with the work done by others, to emphasize especially the new structural and stratigraphic knowledge that has resulted from the drilling of two hundred far-out, and five hundred or more close-in wells, and to show the fault zone patterns and their relations to each other, is the purpose of this paper.

While much of the material presented here is already known, and much has also been prophesied (as recently by Pratt and Lahee[1]), the conclusions herein were independently reached.

We have proven another major zone (the Mexia) in the group of fault zones composed of the Balcones, Mexia, and Palestine which dominate the west limb of the northeast Texas arm of the Gulf Embayment region, and show more fully the structural character of this northwest sector of the Gulf Embayment orogenic unit.

We present, by means of the accompanying correlation table (Plate XIII.), four and a half new sections compiled from new surface surveys and many well logs, showing more fully the characteristics of the stratigraphy, heretofore complicated by lack of knowledge of the faults. These studies have added to our

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[1] See No. 30 in Bibliography at end of paper.

knowledge of the areal stratigraphy of the Navarro, Midway and Wilcox, and have shown the limitations of the Woodbine sands to the south as they had been previously shown on their southwest outcrop. They have demonstrated the rather considerable areal extent of the Pecan Gap chalk member of the Taylor formation, and also have added much regarding the extent and character of the Comanchean formations.

Mr. Robinson, in the second part of this paper, will deal with the origin of the structure and has summarized the literature so as to give due credit for the excellent work done before us. The great work of Dr. Robert T. Hill and the work of Gordon, Stephenson, Deussen, Matson, Udden, Adkins, Winton, and many others, has made possible our own work and that of our staff. To all these workers, as well as to past and present members of my staff,[2] I make grateful acknowledgment.

STRATIGRAPHY.

The chief development of strata is Cretaceous, the Gulf Series being represented by 2,400 to 6,500 feet and the Commanche Series by 750 to 2,100 feet. The Tertiary is represented by 160 to 1,700 feet.

Aside from variations summarized in the accompanying correlation table (Plate XIII.) shown herewith, we wish to give a few of the salient points developed by these investigations. Formations consisting of sand, or largely of sand, are best developed at the north end of the rim of this arm of the Embayment which is nearer the source of such sediments, the Arbuckle and Ouachita Mountains, while shale and limestone formations, as usual, are best developed toward the deeper parts of the basin. Representative of the former are the Travis Peak, Paluxy and Woodbine sands, the Blossom sand member of the Eagleford, and the upper Eagleford shale, all of which are thickest at the north end of the rim. On the other hand, the Glenrose limestone, (thickest at Mexia), Walnut clays, Edwards-Commanche Peak limestones,

[2] H. M. Robinson, S. A. Judson, E. B. Stiles, J. Frost, S. S. Price, W. H. Foster, W. A. Price, C. W. Hammen, and W. A. Reiter.

Dennison beds, Austin chalk, Taylor marls, with its Pecan Gap member, and Navarro, all thicken basinward. The Dennison beds, south of Kosse, are represented by the Del Rio clay which replaces its upper two members; its lower three members are developed on the north and west sides of the rim only. The Buda limestone, which may be the highest member of the Dennison or a separate formation, first appears just northwest of Dallas and thickens basinward, but is unknown on the east rim. The Pecan Gap chalk is well developed as far south as Kosse and has been mistaken for Austin. The Woodbine sands cross the basin probably as far south as Palestine but practically disappear a few miles south of Groesbeck in Limestone County. This formation, especially the basal half, contains much maroon and red shale as far south as Henderson County. Beneath the Commanche series the Pennsylvanian, and possibly some Permian, may occur. Under the northwest sector of the rim, Ellenberger (Ordovician) limestone is present, while along the Balcones fault zone, Udden has identified Pre-Cambrian. Above the Cretaceous, the Tertiary is represented by Midway and Wilcox, both of which thicken basinward.

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GENERAL STRUCTURAL FEATURES.

In a large sense, the district under discussion covers only the northwest sector of the Gulf Embayment. This Embayment is part of a major basin, the extreme bottom of which is the Sigsbee Deep block in the Gulf of Mexico, the Embayment representing the plain extending north of this depressed block. This plain is delimited on the west by a chain of mountains, of which those in East Central Mexico, the Llano-Burnett in Central Texas, the Arbuckles in Oklahoma, and the Ozarks in East Central Missouri, form a part. This chain represents an old major uplift. The corresponding element on the east of the Embayment is the Appalachian chain.

The Gulf Cretaceous of Northeast Texas fills a secondary arm of the Embayment and is the East Texas Syncline of Dr. Hill. This arm lies between the Sabine uplift of Northwest Louisiana and the Llano-Burnett Mountains. The north end of the arm is

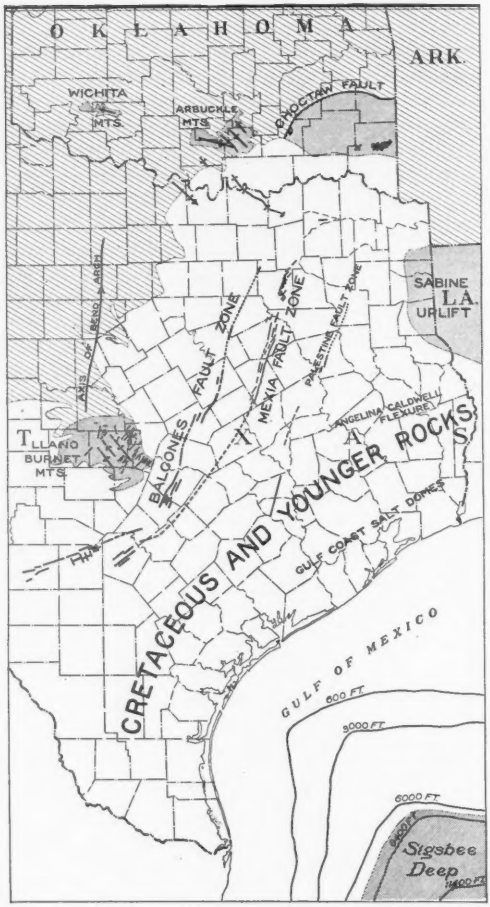
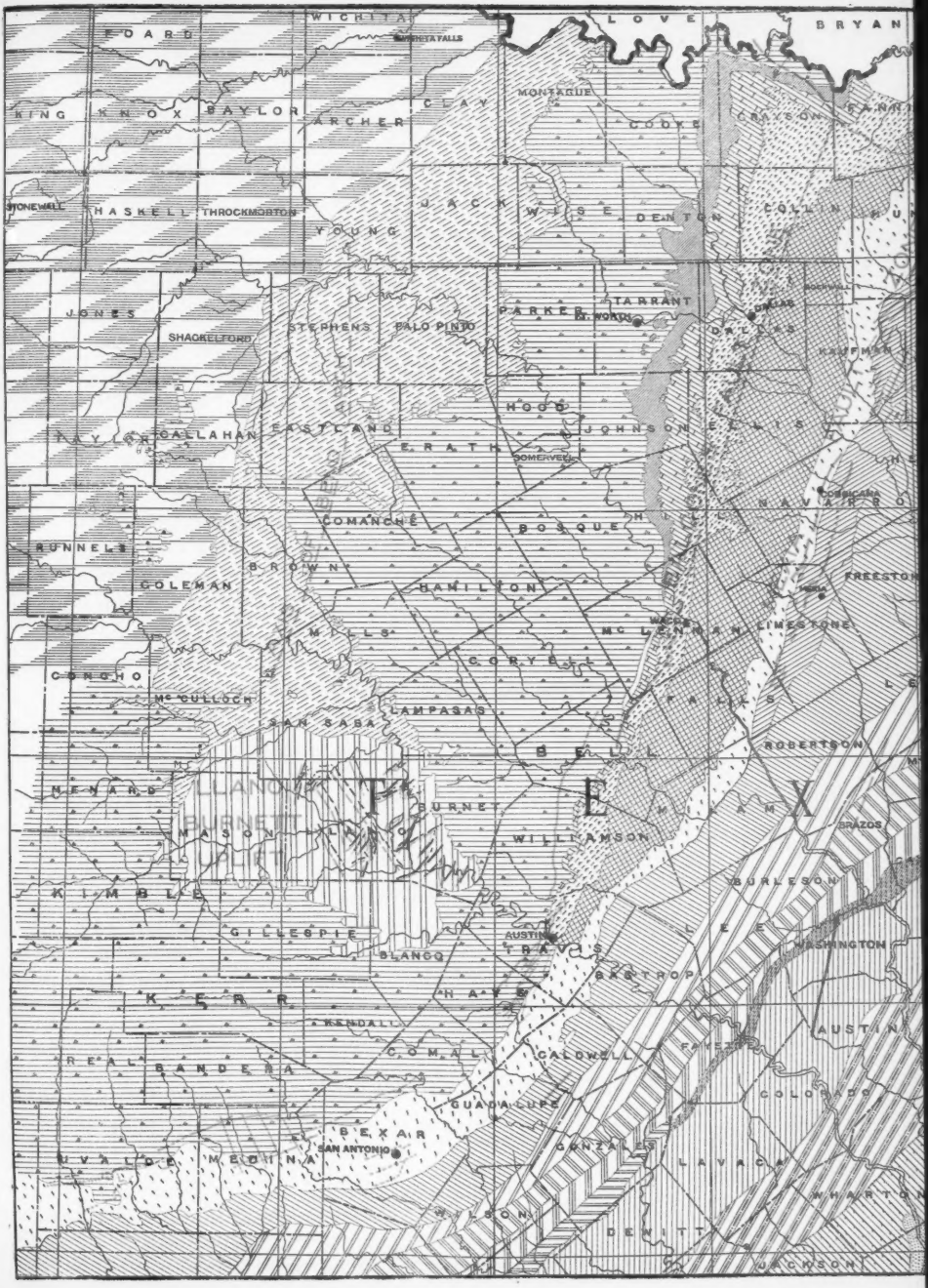


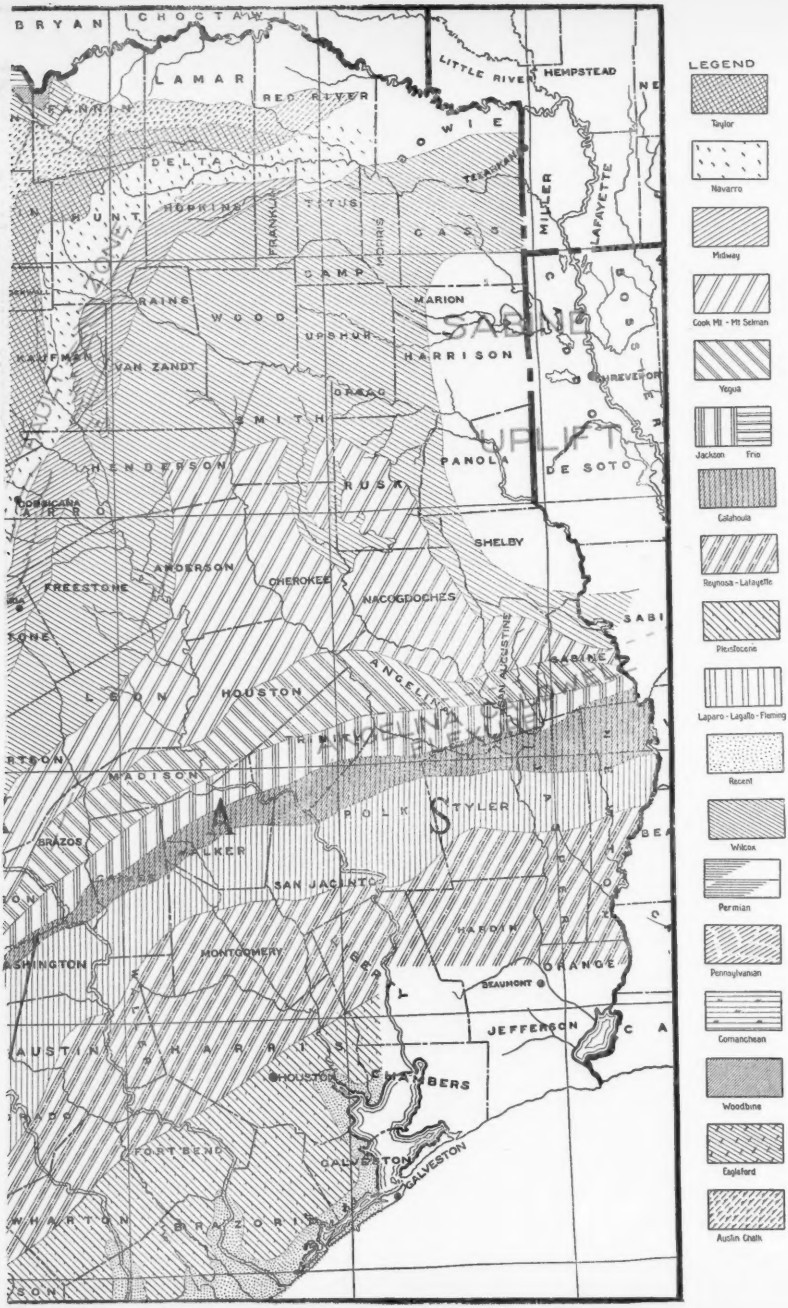
FIG. 104. Sketch map of major structural features surrounding Northeast Texas area.

PLATE XII.



GENERAL STRUCTURAL AND STRATIGRAPHIC MAP OF N

(Legend not arranged in chronologic order



HIC MAP OF NORTHEAST TEXAS.
chronologic order)

delimited by the east-west positive element of the Ouachita Mountain uplift paralleling which, on the north, is the Choctaw fault (displacement 8,000 feet) in Southern Oklahoma and Southern Arkansas. On the south this arm is bounded by the Angelina-Caldwell monoclinal flexure. The Gulf Coastal plain separates this flexure from Sigsbee Deep.

In the northeast arm is the deepest portion of its trough which passes north-northeast through Tyler, in Smith County. The bottom of the trough, just west of Tyler, is disturbed and uplifted, forming the narrow Palestine fault zone with its chain of salt dome islands. Between Tyler and the Sabine uplift the formations appear unbroken in any marked degree. This east limb of the arm, as shown by the cross-section, is shorter than the west limb. The west limb shows strata more gradual but interrupted in two steps by the Mexia and Balcones fault zones. There are, then, three sub-parallel fault zones, each 3 to 15 miles wide as positive elements interrupting east-west this arm of the Embayment.

Crossing the north extension of the East Texas syncline is the dying phase of the Preston anticline, which tends to flatten the strata, north and south along the east-west Midway outcrop. North of this outcrop the strata dip at a steep angle, while south of it, they dip less steeply. Parallel to, and south of, the Preston anticline is a syncline in which a greater thickness of sediments occurs than elsewhere in the northeast Texas arm, except in the synclines east and west of and parallel to the Palestine zone. In these synclines is a series of small folds such as are common in the bottom of a synclinorium.

A secondary zone sometimes appears with a fault of marked displacement as much as five miles east of the east fault of the main zone, as in the vicinity of Streetman and possibly at Eureka.

At Mexia, the faults strike from N. 29° to 40° E., averaging N. 35° E.; at Currie, from N. 13° to 23° E.; at Groesbeck, from N. 10° to 30° E.; at Kaufman, from N. 25° to 54° E.; at Kosse, from N. 15° to 25° E.; and at Powell, about N. 26° E. A

single fault may change its strike several times, but they are not as sinuous as some have thought; thus the main fault on the east side of the Mexia pool has two changes of strike; at Currie, likewise, there are two or more changes, and again at Powell. It is possible that all of these may be one connected fault.

The individual faults, where sufficiently defined, have a length of six miles, though some have been definitely traced only for three miles. Where one of these faults dies out another starts *en echelon,* the interval varying from one-half to one and a quarter miles.

The dips of the main east fault vary, as at Mexia, from 35 to 36° in the upper 2,000 feet and from 50 to 57° below that depth, the dips averaging 43 to 46°. At Currie the dip varies from 53 to 63½°, with a dip possibly as low as 45° locally. It is a coincidence that may be significant that, just above where the change in dip appears in the Mexia fault, there is a slight local anticline shown by the well logs.

The vertical displacement of the east fault at Mexia ranges from 195 to 400 feet; at Currie, 125 to 265, and possibly in excess of 400 feet; at Powell from 245 to 350 feet; in Kaufman, displacements with a maximum of 200 feet appear in the Clarida, Barrow and Fox wells, while the Manning-Grinnan and Abels wells may be faulted near the surface only.

The Balcones zone may extend for a distance of 230 and possibly 470 miles; the Mexia zone is in excess of 200 miles and the Palestine zone 150 miles. The distance between the Llano-Burnett uplift and the Balcones zone is twenty-seven miles; between the Balcones and Mexia zones, from 15 to 30 miles, and between the Mexia and Palestine zones, 30 miles.

The maximum displacements decrease from 1,600 feet, in the Llano-Burnett mountains, to 800 feet, in the Balcones, and to 450 feet, in the Mexia zone, but exceed 3,000 feet in the Palestine zone. Igneous intrusions are known only in proximity to the southwest portion of the Balcones zone.

Oil accumulations in the Woodbine sand and deeper formations apparently occur primarily east of the east fault of the main

PLATE XIII.
SYSTEM
TERTIARY
CRETACEOUS

PLATE XIII.

CORRELATION OF GULF CRETA

GEOLOGIC AGE					CHARACTER OF BEDS
SYSTEM	SERIES	GROUP	FORMATION		
TERTIARY	EOCENE		WILCOX		Sandy and lignitic shales, some quartzose calcareous sand Weathers into red sandy soil and gray sand 0–110
			MIDWAY		Lime-ironstone- and siliceous-concretion bearing shales, partly sandy, fossiliferous limestone and sand Usually weathers into yellowish sandy soil 161–63
	UNCONFORMITY				
CRETACEOUS	GULF SERIES (UPPER CRETACEOUS)		NAVARRO (EXOGYRA COSTATA ZONE)	ARKADELPHIA	Blue to black shales some concretions Sands some-what glauconitic, sandy shales Sandy marls Weathers into b waxey soil exc central sandy p 400–13
				NACATOCH	
			TAYLOR EXOGYRA PONDEROSA ZONE		Predominantly marls with chalky beds near middle and sandy shales and thin sands in lower part Weathers into black waxey soil 130–12
			AUSTIN		Chalk, impure chalk, and hard marls some sandy beds Abundant foraminifera Weathers into black waxey soil 335–1
			EAGLEFORD		Black fissile shales, thin limestones and thin sandston layers. Some bentonite near base Weathers into dark to grey soil sometimes sandy. 30±–
			WOODBINE		Coarse, dark, and maroon shales some sandy shales lea To hard sandstones and earthly lignite about half of form sand Weathers into red and light gray very sandy soil and sand 2–82
	DISCONFORMITY				
	ERIES	WASHITA	BUDA		Fine Textured granular limestone 0–130'
			DENISON		Marls, limestones, and shales, with a middle sandy mem 60–25
			FT. WORTH LIMESTONE		White, thin bedded limestone 21–1
			PRESTON BEDS	DUCK CREEK	Grey limestone and hard marl 7–6
				KIAMICHI	Dark gray shale 7–

CEOUS FORMATIONS OF NORTH-EAST TEXA

DETAILED SECTIONS

GRAYSON COUNTY

stone

0'

5'

lock
apt
ortian

95'

some

50'

Arapa chalk tongue 400-500' transitional waxy clay and marl 400'
Kiker chalk tongue 15-50' Sandy beds cross-bedded sandstones and fine sands with fish bed conglomerate near center 75-90'
Brownstown Marl 300'-350' (1)

195'

zs

907'

e
tion

5'

Dark shales 300'-400' including Blossom Sand (1)

Lewisville beds 150'
Dexter beds 140' (29)

Grayson Marl 15-25' (2)
Main Street limestone 8-20' (2)
Paw Paw sandy member 50' (2)
ver. Weno clay member 115' (2)
Denton clay member 45' (2)

5'?

33' (2)

3'

100' (2)

8'?

40-50' (2)

0'

PARIS-RIPLEY SULPHUR SPGS

Shale 345' (23)

(2)

Limestone fossiliferous 135'+ with sand at base 24' (23-24)

Shale with some sand 535'
Hard sandstone and muddy sands 140'
Shale marly with some sand 90-100' (22)

a Marly shale with marly sand and shale 300'
b Salt cholky beds 30'
Marl occasional hard sand lenses 262' (22)

Hard marl and chalk fossiliferous 30'
Chalky marl sandy 22'
Hard chalk with marl partings 160'
Slightly sandy chalk 70'
Brownstown Marl 110' (22)

Calcareous shale 300'
Marl and sandy chalk 10'
Blossom sand and marl 100'
Calcareous flaky shale 100
Glauconitic sand and shale 18'
Sand some marl beds and thin beds glauconitic sand 379' (22)

Hard sand 2-10'
Water sand some sandy shale 50'
Shale 120'
Water sand 108'
Shale 15'
Water sand & shale 22'
Red and limey sand some shale 227'
Marly sand 10'
Gravel at base 144' (21-22-23)

Unrecorded 100'
Grayish friable sandstone 35'
Impure limestones 25' (21)

TERRELL-WILLS POINT

Sandy shales, quartzose calcareous sandstones lignite, clay ironstone boulders, weathers into rail sandy soils 300+' (14)

Blue shales, lime and ironstone concretions thin pure to sandy fossiliferous limestones with abundant turritella 50' above base, shale and lime concretions 50' to base. Yellowish slightly sandy soils 135' (14-18)

Blue to black shales with some lime concretions near top some sandy shales and thin sands 530-620'
Hard sands 5-35 each water bearing and sandy shales 150'
Blue and sandy shales and marls, glauconitic sands 400' (6-19)

a. Blue and sandy shales and marls, glauconitic sand volcanic ash about 330'
b. Marl and sandy chalk interbedded with some hard and sandy shale 333'
Blue and sandy shale with occasional harder shells 490' (6-19)

Chalky limestone with some shale and sandy pirlic beds near base 578' (6-19)

Sands and limestones alternating with some shale 100'
Sandy shale, shale and some sands near base 240'
Black shales with salt and pepper character at base 145' (6-19)

a. Sands 5-13' thick alternating with dark shales and lignite
b. Dark shales with one 60-70 or two thin sand beds and sometimes maroon shale 70-80'
c. Sands 5-30' each alternating with dark and maroon shales (6) 150'

Hard grayish white marl 120' (13)
Hard white to grey limestone 10' (13)
Sandy limestone 20' (13)
Lime 7'
Shale in lower portion 145' (13)
Hard grayish white limestone 133' (13)
Soft shale (probably part of this formation as represented in both the overlying and underlying formation but unrecognizable due to drifters interpretation 7' (13)
Grey limestones some white limestones and usually showing darker colored streaks along fractures 88' (13)
Shale and boulders 19' (13)

PALESTINE (3)

Sand lenses sandstones, clays sandy clays lignites 450-650' (64)

Marine clays and limestones 250'

Marls, bluish black and glauconitic clays with ironstone concretions yellow and brown sands with hard sandy concretions 600-900'

Blue clay marls 800-1000'

Chalk with thin beds of soft marl 400-500'

Shale and thin arenaceous beds of lamonated limestone 350-400'

(?Woodbine)
Yellow friable and hard ferruginous sandstone, farenaceous clay and clay 350-500' (24)

BETHANY

Clay and sands some gravel and sandstone 195' (64)

Shales 290' (24)

Chiefly shale lime beds in lower half 550'
Gas sand 150'

Shale with concretions 540'

Sand and sandy shale occasionally glauconitic 270'

Sandy marls some sand, gas sand at top and bottom 265' (24)

Marly shale 130' (24)

BINGEN
Sandstone with interbeded shales 116'
Shales with limestones in lower one third 377'

Broken lime some sand and hard limestones with 25 feet hard shale and shells at base 342'
Red shales 115'
Shale and shells 35'
Broken sand shells and rock 50'
(24) (49)
Hard and broken limestone 34'
Sandstone 31'
Hard and soft shale 60'

CORSICANA-EUREKA

Shale with concretions 267'
Sandy limestone 57'
Shale and concretions 50'
Sand 20' (12-16-17)

Shale with concretions 540'

Sand and sandy shale occasionally glauconitic 270'

Sandy marls some sand, gas sand at top and bottom 265'

a Marly shale with sand and sandy shale lower half 429'
b. Marls chalky marls sandy shale 989'
Sandy shale some sand marls and chalk boulders lower half 362'
Sand at Base 2-5' (12-16-17)

Chalk with occasional sandy layers 425-465'
Shale, sand usually water bearing sandy shale and thin chalk 70' (12-16-17)

Black shale concretions and sandy shale with sandy lime shells at base 300' (12-16-17)

Principal sand beds some sandy shale, thin shale lime and grey shale layers 156'
Shale 54'
Sands some blue to black shale sandy shales and limestones interbeded 134'
Sand sandy lime water sand some lignitic shale 52' (12-16-17)

Lime 10'
Bluish black shale 50'
Hard lime 80'
Broken sand 8'
Black Shale 57' (49)

Hard gray lime 25'
Hard gray lime and very hard marl 80' (15)
Black shale (sandy) 38' (49)

105'

MEXIA

Shales containing limestone and clay-ironstone concretions sandy and fossiliferous limestone 300+'
Sandy shale & sand 50' (50)

Shale, some sand 600-615'

Nacatoch gas sand horizon, sandy and fossiliferous with interbeded limestone and sandy shale 175'
Shale with 10ft oil sand at base 160' (50)

a Shale 525'
b Sandy chalk & marl 255'
Sand 20'
Chalky horizon some sandy shale 130'
Shale with sandy shale in lower half 320' (31)

Chalk occassionally some sandy chalk 385'
Shale and chalk with sand 50' (50)

Black fissile shale some limestone layers 210' (50)

Sandstone some lime with black shale and sandy shale with 40' sand at base 143-165'
Shale 2-12'
Water sand 10'
Blue shale with a little sand and sandy shale 100'
Lime and sandstone with oil in basal portion (31) 30'

Shale with thin lime layers 50'
Limestone with fine texture 80' (9)
Del Rio Clay dark blue in color 40' (9)
Gray shale 37' (9)

White fine textured limestone 23' (9)
Gray clayey limestone 42' (9)
White limestone and dark shale 13' (9)

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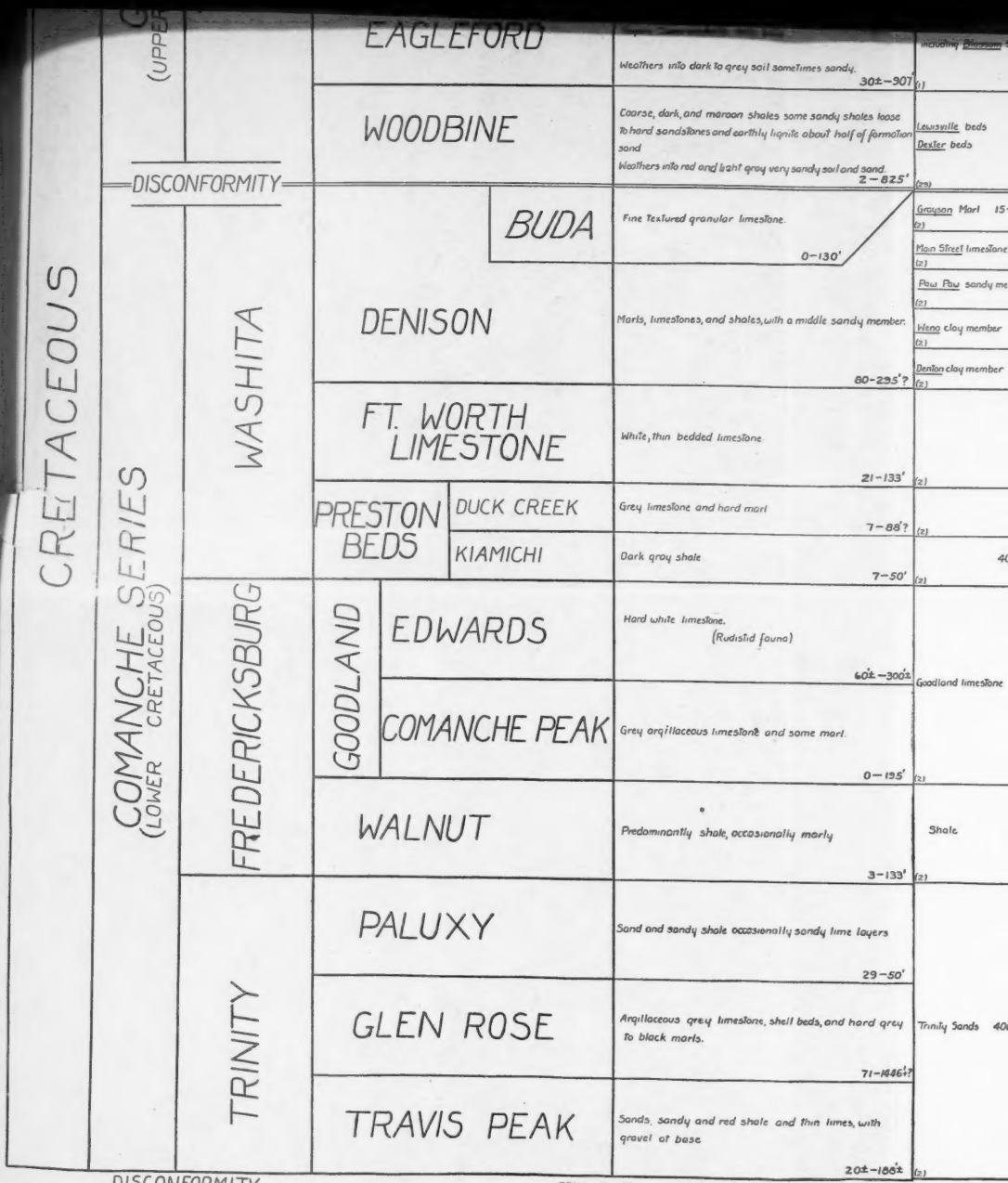
(11)

T TEXAS

By F JULIUS FOHS

T MEXIA	KOSSE	AUSTIN (7)
	Shale and hard boulders (Mostly Midway) 400'	
Shales containing lime-stone and clay-ironstone concretions sandy and fossiliferous limestone 300+ Sandy shale & sand 50' (30)	Broken limestones and sandstones 70-120' (10-11)	LYTTON 300' Clay sand and sandstone
Shale, some sand 600-615'	Shale and some boulders 630'	
Nacatoch gas sand horizon, sandy and fossiferous with interbedded limestone, and sandy slage 175' Shale with 10ft oil sand at base 160' (30)	Gas sand at Top sand shale, and thin sandstones -230'	WEBERVILLE 400' Black shaley bituminous clay and green sands
a Shale 525' b Sandy chalk & marl 235' Sand 20' Chalky horizon some sandy shale 130' Shale with sandy shale in lower half 320' (31)	Shale limey towards base some sandy shale 450' b Chalk, sandy chalk some shale 300' Marls volcanic ash with sandy shale in lower one third 295' (10-11)	Marls 540'
Chalk occassionally some sandy chalk 385' Shale and chalk with sand 50' (30)	Chalk, abundant foraminifera 335' (10-11)	Chalk 410'
Black fissile shale some limestone layers 210' (30)	Bluish-black flaky shales with thin layers of sand- and limestone-shells near base 330' (10-11)	Black shales 30'±
Sandstone, some lime with black shale and sandy shale with 40' sand at base 149-165' Shale 2-12' Water sand 10' Blue shale with a little sand and sandy shale 100' Lime and sandstone with oil in basal portion (31) 30'	Sandy shale 2-5' sometimes absent (10-11)	Absent
Shale with thin lime layers 50'	Hard fine textured limestone sandy in parts 113' (10-11)	Pink limestones 45'
Limestone with fine texture, 80' (9)		
Del Rio Clay dark blue in color 40' (9)	Dark shale with lime-shells 101' (10-11)	DEL RIO Clay 80'
Gray shale 37' (8)		
White fine textured limestone 23' (8)	White lime 21' (10-11)	GEORGETOWN Limestone 80'
Gray clayey limestone 62' (8)	White lime 48' (11)	
White limestone and dark shale 13' (8)	Shaley lime 7' (11)	



DISCONFORMITY

PERMIAN & PENNSYLVANIAN

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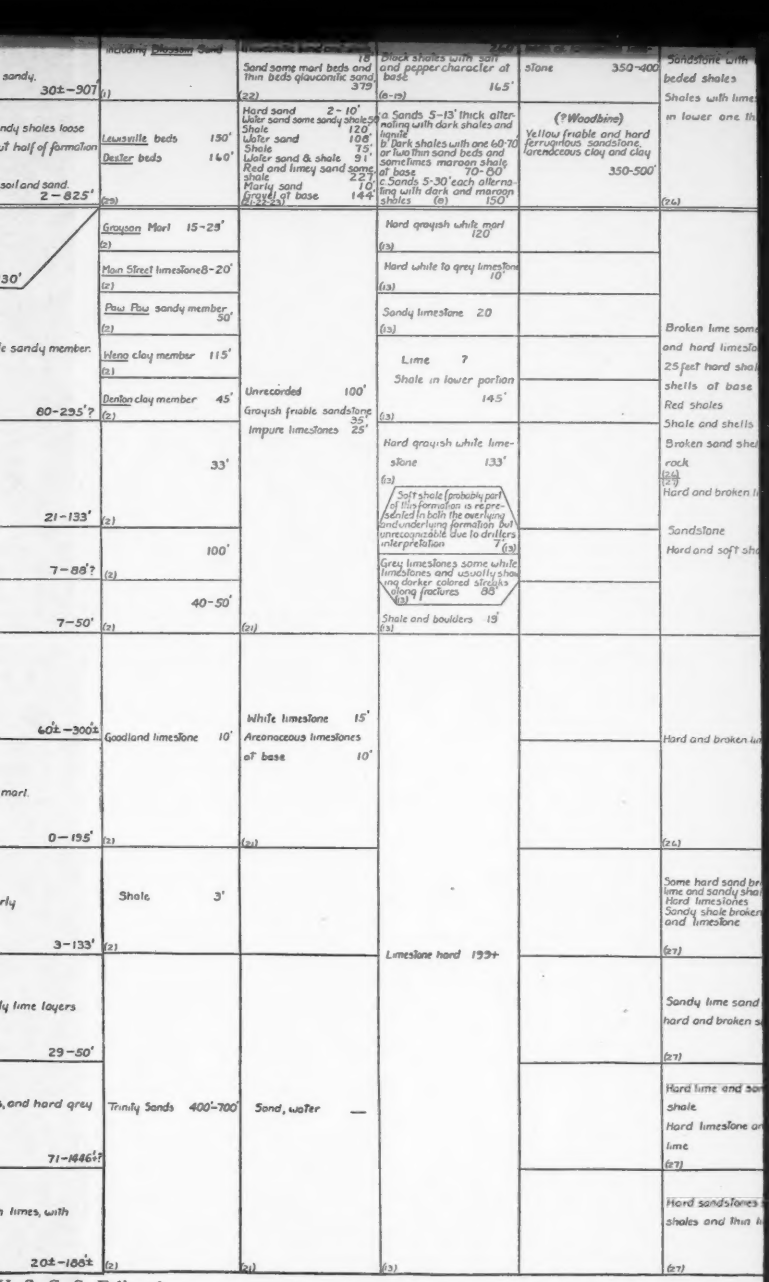
9. Humphreys Oil Co. A. E. Berthelson No. 36, Mexia, Lim stone Co.
10. Humphreys Oil Co. Jones No. 1, Kosse, Limestone Co.
11. Humphreys Oil Co. Bassett No. 1, Kosse, Limestone Co.
12. Humphreys Oil Co. Singleton No. 1, Eureka, Navarro Co.
13. Magnolia Pet. Co. Cernoch No. 1, 5 miles NW. Terrell, Kau man Co.
14. Walker Consol. Dawson No. 1, 5 miles S. Wills Point, Va Zandt Co.

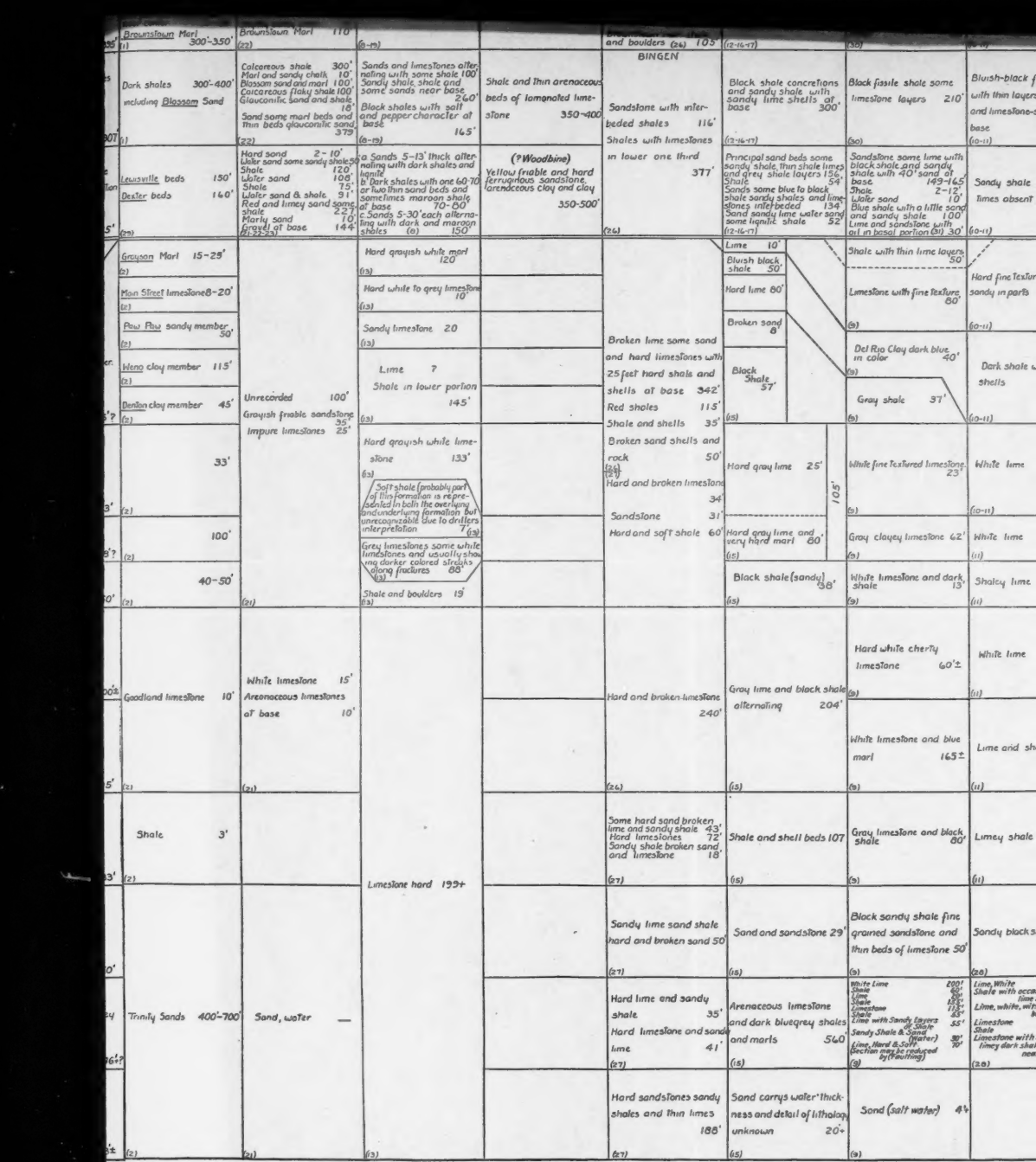


U. S. G. S. Folio 76.
Elmo, Kaufman Co.
lson No. 36, Mexia, Lime-

Kosse, Limestone Co.
Kosse, Limestone Co.
1, Eureka, Navarro Co.
5 miles NW. Terrell, Kauf-

miles S. Wills Point, Van

15. Cortex Oil Co. Gray No. 1, Corsicana, Navarro Co.
16. Brandon & McCamey J. J. Stubbs No. 1, Currie, Navarro
17. Lee Frazier No. 1, 5 miles So. Richland, Pisgah Ridge, Nav
Co.
18. Tucker Boshea No. 1, East Central Kaufman Co.
19. Panhandle Refining Co. Manning-Grinnan No. 1, Kaufman
20. City Well, Terrell, Kaufman Co.
21. City of Paris, Lamar Co.—(Gordon-Hill correlation).
22. Humphreys Oil Co. Corey No. 1, Titus Co. (macroscopic
by Stiles).

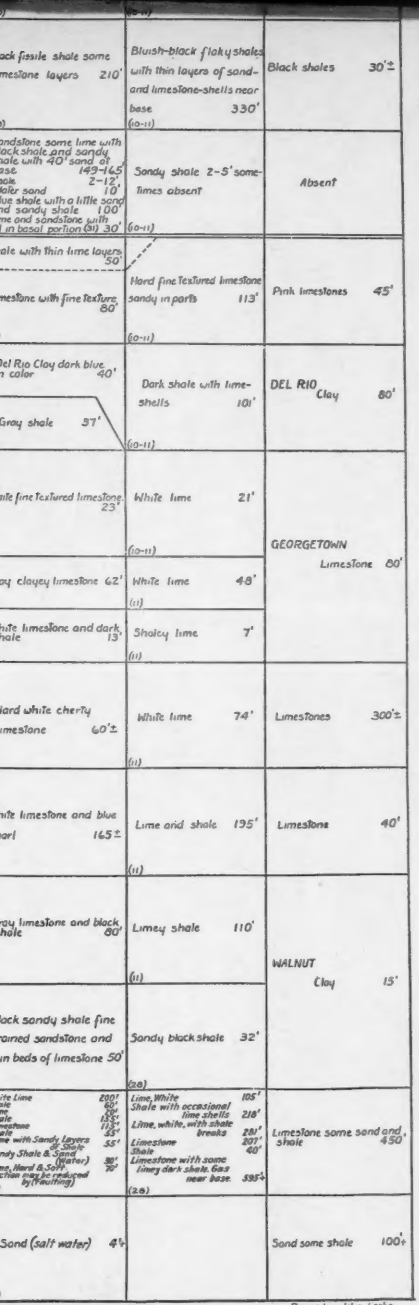

Brownstown Marl 300'-350' (1)
Dark shales 300'-400' including Blossom Sand (1)
Lewisville beds 150' Dexter beds 140' (23)
Grayson Marl 15-29' (2)
Main Street limestone 8-20' (2)
Paw Paw sandy member 50' (2)
Weno clay member 115' (2)
Denton clay member 45' (2)
33' (2)
100' (2)
40-50' (2)
Goodland limestone 10' (2)
Shale 3' (2)
Trinity Sands 400'-700'
Brownstown Marl 110' (22)
Calcareous shale 300' Marl and sandy chalk 10' Blossom sand and marl 100' Calcareous flaky shale 100' Glauconitic sand and shale 18' Sand some marl beds and thin beds glauconitic sand 379' (22)
Hard sand 2-10' Water sand some sandy shales 95' Shale 120' Water sand 108' Shale 75' Water sand & shale 91' Red and limey sand some shale 225' Marly sand 10' Gravel at base 144' (21, 22, 23)
Unrecorded 100' Grayish friable sandstone 35' Impure limestones 25' (21)
White limestone 15' Arenaceous limestones at base 10' (21)
Sand, water —
(6-19)
Sands and limestones alternating with some shale 100' Sandy shale, shale and some sands near base 260' Black shales with salt and pepper character at base 165' (6-19)
a Sands 5-13' thick alternating with dark shales and lignite b Dark shales with one 60-70' or two thin sand beds and sometimes maroon shale at base 70-80' c Sands 5-30' each alternating with dark and maroon shales (c) 150'
Hard grayish white marl 120' (13)
Hard white to grey limestone 10' (13)
Sandy limestone 20 (13)
Lime 7 Shale in lower portion 145' (13)
Hard grayish white limestone 133' (13)
Soft shale (probably part of this formation is represented in both the overlying and underlying formation but unrecognizable due to drillers interpretation 7' (13)
Grey limestones some white limestones and usually showing darker colored streaks along fractures 88' (13)
Shale and boulders 19' (13)
Limestone hard 199+
Shale and thin arenaceous beds of laminated limestone 350-400'
(?Woodbine) Yellow friable and hard ferruginous sandstone, arenaceous clay and clay 350-500'
Shale and boulders (24) 105'
BINGEN
Sandstone with interbedded shales 116' Shales with limestones in lower one third 377' (26)
Broken lime some sand and hard limestones with 25 feet hard shale and shells at base 342' Red shales 115' Shale and shells 35' Broken sand shells and rock 50' (24) (27) Hard and broken limestone 34' Sandstone 31' Hard and soft shale 60'
Hard and broken limestone 240' (24)
Some hard sand broken lime and sandy shale 43' Hard limestones 72' Sandy shale broken sand and limestone 18' (27)
Hard lime and sandy shale 35' Hard limestone and sand lime 41' (27)
Hard sandstones sandy shales and thin limes 188' (27)
(12-16-17)
Black shale concretions and sandy shale with sandy lime shells at base 300' (12-16-17)
Principal sand beds some sandy shale, thin shale lines and grey shale layers 156' Shale 54' Sands some blue to black shale sandy shales and limestones interbedded 134' Sand sandy lime water sand some lignitic shale 52' (12-16-17)
Lime 10' Bluish black shale 50' Hard lime 80' Broken sand 8' Black Shale 57' (15)
Hard gray lime 25' 105' Hard gray lime and very hard marl 80' (15)
Black shale (sandy) 38' (15)
Gray lime and black shale alternating 204' (15)
Shale and shell beds 107 (15)
Sand and sandstone 29' (15)
Arenaceous limestone and dark blue grey shales and marls 540 (15)
Sand carrys water thickness and detail of lithology unknown 20+
(30)
Black fissile shale some limestone layers 210' (30)
Sandstone some lime with black shale and sandy shale with 40' sand at base 149-165' Shale 2-12' Water sand 10' Blue shale with a little sand and sandy shale 100' Lime and sandstone with oil in basal portion (31) 30' (30-11)
Shale with thin lime layers 50' Limestone with fine texture 80' (9)
Del Rio Clay dark blue in color 40' (9) Gray shale 37' (9)
White fine textured limestone 23' (9)
Gray clayey limestone 62' (9)
White limestone and dark shale 13' (9)
Hard white cherty limestone 60'± (9)
White limestone and blue marl 165± (9)
Gray limestone and black shale 80' (9)
Black sandy shale fine grained sandstone and thin beds of limestone 50' (9)
White Lime 200' Shale 60' Lime 50' Shale 125' Limestone 115' Shale 45' Lime with Sandy Layers of Shale 55' Sandy Shale & Sand (Water) 30' (Lime, Hard & Soft Section may be reduced by faulting) 70' (9)
Sand (salt water) 4+ (9)
Bluish-black f with thin layers and limestone base (10-11)
Sandy shale Times absent (10-11)
Hard fine Textur sandy in parts (10-11)
Dark shale shells (10-11)
White lime (10-11)
White lime (11)
Shaley lime (11)
White lime (11)
Lime and sh (11)
Limey shale (11)
Sandy black s (20)
Lime, White Shale with occa lime Lime, white, wit h Limestone Shale Limestone with limey dark shal new (20)

. Folio 76.
man Co.
86, Mexia, Lime-

estone Co.
estone Co.
Navarro Co.
W. Terrell, Kauf-

Wills Point, Van

15. Cortex Oil Co. Gray No. 1, Corsicana, Navarro Co.
16. Brandon & McCamey J. J. Stubbs No. 1, Currie, Navarro Co.
17. Lee Frazier No. 1, 5 miles So. Richland, Pisgah Ridge, Navarro Co.
18. Tucker Boshea No. 1, East Central Kaufman Co.
19. Panhandle Refining Co. Manning-Grinnan No. 1, Kaufman Co.
20. City Well, Terrell, Kaufman Co.
21. City of Paris, Lamar Co.—(Gordon-Hill correlation).
22. Humphreys Oil Co. Corey No. 1, Titus Co. (macroscopic log by Stiles).
23. Deering No. 1, Sulphur Springs, H
24. Noco. Smiddy No. 1, Hopkins Co.
25. Cousens-Hall, Stough No. 2, Hopkins
26. Aaron Jeter No. 1, Bethany, Panol mill).
27. Gulf Producing Co. Augurs No. 1, 2 Parish, La. (after Sidney Powers).
28. Humphreys-Texas Co. Welch No. 1,
29. After Robert T. Hill.
30. Humphreys Oil Co. Mary Focke Co.



Drawn by- John Lorke

o. 1, Sulphur Springs, Hopkins Co.
ddy No. 1, Hopkins Co.
ll, Stough No. 2, Hopkins Co.
r No. 1, Bethany, Panola Co. (after C. A. Ham-

cing Co. Augurs No. 1, 2 miles NE. Jeter in Caddo
. (after Sidney Powers).
-Texas Co. Welch No. 1, Limestone Co.
rt T. Hill.
Oil Co. Mary Focke No. 1, Mexia, Limestone

zone, as at Mexia, Currie, Seay-Cranfill and Kosse pools but very limited pools such as the new Morrow pool south of Currie may occur on the west or downthrow side of this fault. The faulting and folding west of this fault show oil and gas in the shallower sands at depths of less than 1,350 feet or none at all. Shallow oil only is known in the Balcones zone at south Bosque and Thrall.

Balcones Fault Zone.—Primarily to the work of Dr. Robert T. Hill credit is due for our knowledge of the Balcones Fault Zone and much of what I give below is taken from a summary supplied by him in a private communication, though the works of Miss Lula Pace, in McLennan County, and of others, have contributed details

The use of the term " Balcones " should be restricted, however, to the zone of faulting extending east-west for a width of five to fifteen miles, and north-south from San Marcos northeast through Rockwall County, and southeast from San Marcos to Uvalde and Del Rio. The maximum width is north of Hondo. This zone, in general, follows the outcrop of the Austin chalk though locally cutting at the surface through the next underlying or overlying shale series.

Lahee and Pratt, following Hill, have indicated a broader usage, including the Mexia and Palestine fault zones, where we consider these distinct or sub-parallel zones though related both in origin and age. While some of the shale-sand covered areas intervening between these zones may contain other zones of faulting or individual faults, it is doubtful that such occurrences are sufficiently marked to warrant the inclusion of the whole as one zone. The absence of material faulting between the Mexia and Balcones zones is, in our opinion, proven by the absence of connate Woodbine waters west of the immediate vicinity of the east fault of the main Mexia zone.

Northwest of the Balcones zone, from the northern line of Travis County southwest to the Rio Grande, at the mouth of the Pecos River, an escarpment of hills and mountains rises 200 to 1,000 feet above the valley east of them. At the foot of this escarpment the principal displacement appears and forms the west

boundary of the zone. The fact that the Balcones Hills form part of this escarpment suggested originally to Dr. Hill the name of the zone.

The zone is limited nearly everywhere on the west by a major fault with a displacement of 100 to 800 feet. It is, in reality, a series of short faults overlapping *en echelon*. The many subordinate faults have sub-parallel directions, all concentrated within a narrow belt of country.

The general character of the fault zone is shown in the illustrations and maps of Hill's Geology of the Black and Grand Prairies and Geology of the Edwards Plateau and Rio Grande Plain, and in the Austin, Brackett, and Uvalde folios of the Geologic Atlas of the Geological Survey. By an examination of these cross-sections of the faulted belt it will be seen that towards the west there are major faults of larger downthrow, accompanied, to the east, by numerous smaller ones. The effect of the numerous faults is to break the regularity of the dip of the strata and to chop them into numerous blocks tilted at various angles within the zone. The sum of all the faults amounts to a general downthrow of hundreds of feet. At Austin, thirteen faults occur in five and a half miles, half dipping west and half east, averaging 50° dip—all normal faulting, with one displacement of 800 feet.

In Uvalde County, west of the Nueces River, these fault blocks are replaced by a monoclinal flexure, but still further westward, in Valverde County, they appear only as small subordinate folds. North of Georgetown the character of the fault zone is less well marked because it cuts through the shales underlying the Austin chalk. At Belton, west of Georgetown, the faults are well shown in the valleys of Nolan and Lampases Rivers, but the details have not been mapped.

In the vicinity of Waco the fault zone may be seen in the Austin chalk and the details here have been mapped by Miss Pace. North of Waco it passes into the unconsolidated clays of the Black Prairie, between Whitney and Aquilla, where there are traces of a fault zone, but displacements are not proven.

East of Forreston, in Ellis County, there are faulted folds in the Austin chalk which have the position and trend of the Balcones

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fault zone. The crests of these folds are faulted. Brantly has recognized a zone of minor faulting in the Eagle Ford formation east of Venus, near the Johnson-Ellis County line, which is approximately within the supposed extension of this zone. Numerous small fractures and slopes were noted by Shuler and ourselves in the Austin chalk in the vicinity of DeSoto, in Dallas County, which probably are the representatives of this zone, extending northeast to the east of Dallas.

The sandstone dike intruding the joint clays in the south edge of Rockwall has the characteristic N. 30° E. trend of the Balcones fault zone. North of this point traces of the zone are not abundant in the soft strata extending toward Red River.

Extensive displacements in the Austin chalk are to be seen near the village of Westminster, in northern Collins County, in line with the trend of the Balcones fault zone, while the so-called "Ector tongue" in the northern part of western Collin County, as mapped by Stephenson, is thought by Hill to be probably in line with the zone.

The average strike of the faults of this zone is about N. 30° E.

In a drill hole at Georgetown, below 1,250 feet, and in another two miles northeast of Leon Springs, in Bexar County, below 1,000 feet, material regarded by Dr. J. A. Udden as Pre-Cambrian suggests the uplift in connection with the Balcones to have begun in Paleozoic time, Pennsylvanian beds being absent.

According to Hill, not the least interesting features of the Balcones fault zone are the volcanic necks or stocks that occur intermittently between Thrall, in Williamson County, and Moro Mountain, Kinney County. There are small vertical necks, stocks and dikes of Nepheline basalt that intrude into the Cretaceous strata and which, in most instances, are exposed by erosion. In one case, at Thrall, Williamson County, the material was exposed by the drill, and it was found to be porous material containing oil in commercial quantities. The possible presence of similar necks beneath the interior salt domes of East Texas may satisfy certain hypothetical conditions concerning the latter phenomena. South and east of Austin, igneous rocks are noted at Pilot Knob and in small plugs.

An interesting feature of the Balcones fault zone is the abrupt change from northeast-southwest to east-west direction which takes place in the vicinity of New Braunfels and San Antonio. It has been suggested, by Hill, that instead of this being a bend, it may be a crossing place of two distinct fault zones, one of which may continue southwest towards Laredo and the other east towards Sabine Lake. If this speculation should ever be proven, and it should be proven that such an eastward continuation of the fault line exists, it may be found that many of the oil productive coastal salt domes lie along this projected hypothetical line.

Mexia Fault Zone.—While some faulting had been noted by Hill and Deussen, most of the details and present conception of a distinct zone of faulting were developed as a result of the recent active search for oil pools. This zone is sub-parallel to the Balcones and is from five to nine miles wide. The Navarro shale valley bordering the more resistant Midway limestone ridge forms a marked escarpment on the west side of the zone through much of its course. Another more or less marked ridge occurs usually just east of the major east fault of the zone, while some of the larger intermediate faults, because of their limestone caps, may form intermediate, but less marked, ridges. East of the east ridge. still another well-marked ridge appears, usually capped with Wilcox red sands and clays. This zone consists of a main zone, five to six miles wide, and a secondary zone on the east, appearing only locally for a width of five miles. The main zone is characterized by Navarro shale on the west, offsetting Midway limestone, with a major displacement of as much as 400 feet limiting the west side of the zone, dipping east. On the east of the zone there is again a major vertical displacement of 125 to 400 feet, which dips west.

Beginning on the west side, this zone consists of a series of fault blocks one quarter, one half, one and two miles wide, the last being a "graben." The blocks are, on the average, about one and a quarter miles wide. The arrangement is that of two anticlines separated by a syncline. The west anticline is much faulted on its west limb, with the "graben" block synclinal, and the east anticline faulted east of its axis on the east side of the "graben." Both anticlines show local domes

A secondary zone sometimes appears with a fault of marked displacement as much as five miles east of the east fault of the main zone, as in the vicinity of Streetman, and possibly west of Eureka.

At Mexia, the faults strike from N. 29° to 40° E., averaging North 35° E.; at Currie, from N. 13° to 23° E.; at Groesbeck, from N. 10° to 30° E.; at Kaufman, from N. 25° to 54° E.; at Kosse, from N. to E. A single fault may change its strike once or twice, but they are not as sinuous as some have thought; thus the main fault on the east side of the Mexia pool has two changes of strike while at Currie a single strike is probable, through the Seay-Cranfill fault may be separated from the Currie fault.

The individual faults, where sufficiently defined, have a length of six miles, though some have been definitely traced for only three miles. Where one of these faults dies out, another starts *en echelon*, the interval varying from one half to one and a quarter miles.

The dips of the main east fault vary, as at Mexia, from 35 to 36° in the upper 2,000 feet and from 50 to 57° below that depth, the average being 43 to 46°. At Currie the dip varies fro. 53 to 63½°, with a dip possibly as low as 45° locally. It is a coincidence that may be significant that, just above where the change in dip appears in the Mexia fault, a slight local anticline is shown by the well logs.

The vertical displacement of the east fault at Mexia ranges from 195 to 400 feet; at Currie, 125 to 265, and possibly in excess of 400 feet; in Kaufman, displacements with a maximum of 200 feet appear in the Clarida, Barrow and Fox wells, while the Manning-Grinnan and Abels wells may be faulted near the surface only. The displacements were noted in the first three wells at depths of 1,500 to 3,000 feet by shortening of the usual stratigraphic interval. Other wells, in Kaufman, Hunt and Van Zandt, show no certain evidence of faulting.

As proof that the east fault at Mexia and Currie follows an anticline, the beds east of the fault dip gently east, except locally, where there is secondary doming—where they also dip for a short

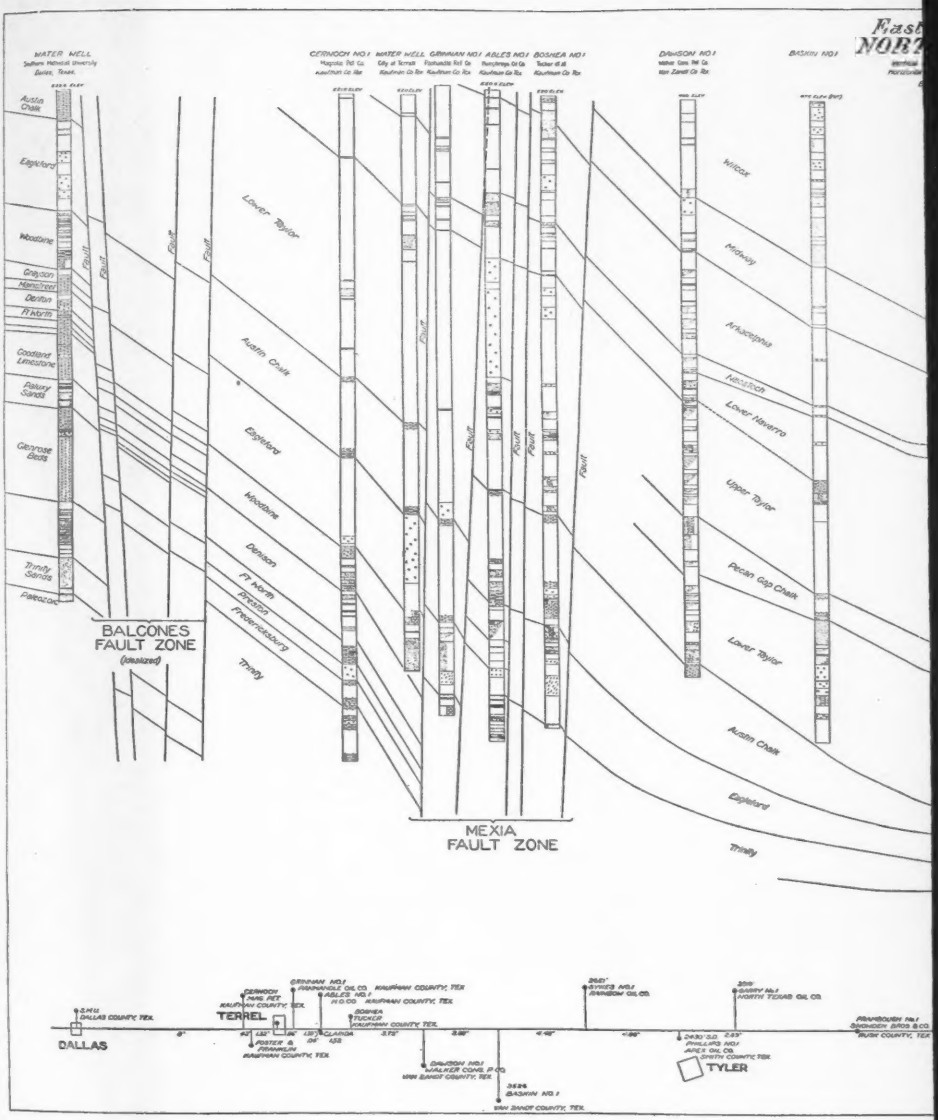
distance west toward the fault. West of the fault they dip more steeply west—from steeply at the fault to less steeply further west. This dip at Currie and Mexia west of the fault varies from 1 foot in 14 feet to 1 foot in 32 feet.

Palestine Fault Zone.—A group of saline domes, somewhat similar in type but apparently unrelated to those of the Gulf Coast area, appears in a general zone (with one exception) which we first designated as the Palestine structure but now call the Palestine fault zone. We have reached the conclusion that it is a fault zone in general, parallel to the Mexia and Balcones zones, because we can conceive of no other condition that would bring into juxtaposition the much older and younger beds such as appear in the vicinity of some of these domes. This zone parallels the bottom of the East Texas syncline. There is still some doubt on which side of this zone is the lowest portion of this syncline.

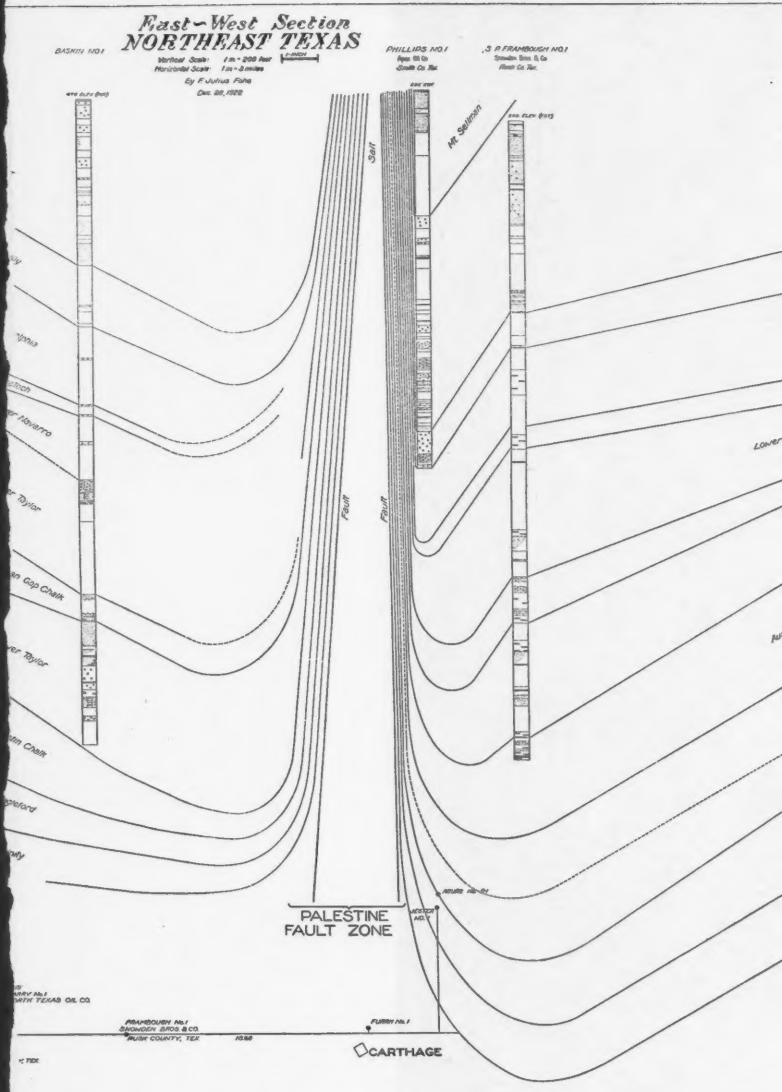
Substantial oil accumulations in the Woodbine sand and deeper formations apparently occur principally east of the east fault of the main zone as at Mexia, Currie, Seay-Cranfill, and Kosse pools with rare accumulations as at the Morrow pool immediately west of it. The faulting and folding west of this fault shows oil and gas in the shallower sands at depths of less than 1,350 feet or none at all. The characteristics of the waters of the Woodbine sand horizon, as shown by the table herewith, are as follows:

Locality.	Parts per Million Solids.	Primary Salinity, Per Cent.	Secondary Salinity, Per Cent.	Primary Alkalinity.	Secondary Alkalinity.	Per Cent. Sulphate, rSo^4+rC^1.
Dallas.....	1,478	29.2	2.2	0.0	68.60	50.3
West of Mexia Fault Zone....	9,700 to 13,272	89.60—93.98	0.0	3.42–8.56	1.84–2.68	0.04–0.13
Currie Pool.....	15,400 to 21,400	91.98—96.36	1.70–3.92	0.0	1.00–5.50	0.00–0.25
West of Currie Pool Fault....	18,561	95	4.2	0.0	0.8	0.1
Mexia Pool.....	20,000 to 35,388	90.00—93.88	4.88–9.12	0.0	0.90–1.52	0.06–0.30
Kosse.....	39,529	91.9	6.4	0.0	1.7	0.9
McCoy (Barrow)	52,455	91.60	6.70	0.0	1.7	0.16
Kerens.....	25,804	95.38	2.22	0.0	2.40	0.02
Smiddy.....	51,106	93.86	5.82	0.0	0.32	0.12
Corey	68,337	94.60	5.10	0.0	0.03	0.0

PLATE XIV.



EAST-WEST CROSS SECTION ON WELL



ROSS SECTION ON WELL LOGS ACROSS NORTHEAST TEXAS ARM OF GULF EMBAYMENT.

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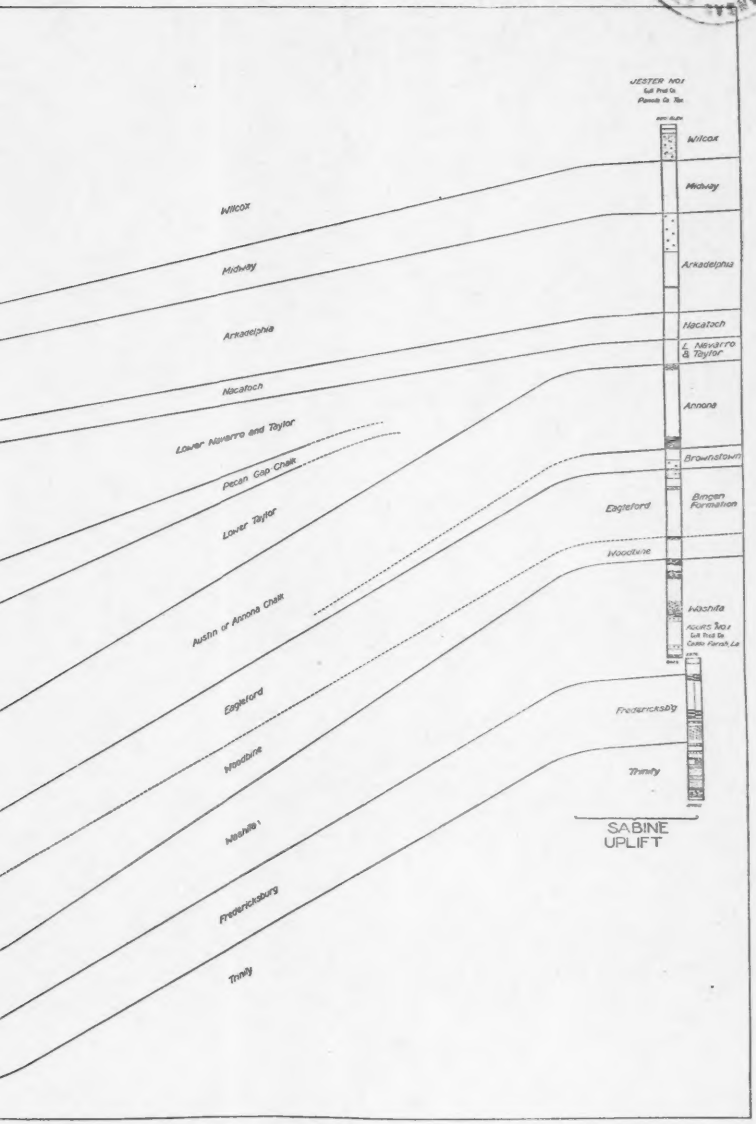

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From some fifty analyses of waters from the Woodbine sand, we find meteoric waters only west of the Balcones zone, mixed waters between the Balcones and Mexia zones and somewhat modified waters with a solid content as low as 14,500 parts per million to a maximum of 35,000 parts solids, usually with the oil.

The characteristics of the waters of the Woodbine sand horizon as shown by the table herewith are as follows: West of the Balcones fault zone the water is meteoric with less than 1,500 parts solids per million, low primary and secondary salinity, high secondary alkalinity and very high sulphate content. Between Mexia and Balcones zones much modified water appears with a solids content below 13,300 parts, but primary salinity is high and secondary alkalinity and sulphate content is low.

The solids content in the Mexia pool waters ranges from 20,000 to 36,000 parts; at Currie pool (on both sides of east fault) somewhat modified waters, with 15,000 to 21,400 parts, and elsewhere both east and west of the main fault in the Mexia zone connate waters, with 25,000 to 52,000 parts. All these waters have high primary and secondary salinity (except Currie, where the secondary is intermediate), no primary, and low secondary alkalinity, and but a small fraction of 1 per cent. of sulphate content—none are associated with oil below a solid content of 14,500 parts as at Powell. Water from the base of Woodbine sands shows higher solids content, as does Buda water, while Trinity water carries high primary and high secondary alkalinity.

There is some evidence of trapped waters west of the east fault of the Mexia zone, as at the Barrow well in Kaufman County, with a more concentrated brine than in the oil pools, and weaker brines east of the oil pools; the method of trapping the former and of modifying the latter requires further investigation, though weaker brines are more readily explicable on the basis of parallel faulting than the concentrated brines.

THE ORIGIN OF THE STRUCTURE.

BY H. M. ROBINSON.

The purpose of this part of the paper is to show the principal factors that are believed to have been instrumental in producing the structure shown on the maps and described in the first part of this paper. Some of the ideas here treated have been presented previously so that the following represents, part, amplification of former views with, perhaps, some additional conclusions made possible by new data.

Analysis of Stresses.—The late Joseph Barrell taught in the classrooms of Yale University that the forces producing the majority of faults could be resolved into two kinds: one, a compressive force, acting in a horizontal direction, and the other, a vertical force, acting at right angles to the horizontal force. It is recognized that movements along a single fault plane may have been at various directions at different times but the sum total of these movements may be resolved into two components, one acting in a horizontal direction, the other in a vertical direction. If the vertical force is just enough to cause a break and the compressive force much less than the vertical, the break will be along a plane making a 45° angle with a horizontal plane; if both forces are strong and nearly equal, with the vertical somewhat in excess, the fault plane will be inclined to be vertical. If the horizontal force greatly exceeds the vertical, a great overthrust fault could be produced. Thus a fault or a series of faults at one locality will be normal and at another locality overthrust if the dominance of the vertical and horizontal forces are different in the two localities. It is believed that the above principles are applicable to the area under consideration.

Character of Stresses.—The Mexia fault zone is characterized by normal faulting and the vertical displacements in the Upper Cretaceous rocks are as a rule in the neighborhood of 200 feet. Where sufficient data are available to measure the angles made by the fault planes with the horizontal, it is found that the angles are in some cases about 45°, if the measurement is made from where

the surface rocks are cut to where the Woodbine sand is cut. Cross sections in the Mexia field indicate that hard chalk or limestones and sandstones have been broken off at steeper angles than the soft clays and shales. This is logical because the limestones are relatively rigid and the shales would tend to drag near the fault planes. It may be concluded, then, that the faulting in the Mexia fault zone in the Upper Cretaceous rocks was caused by dominant vertical forces which found relief after a vertical displacement of the rocks of about 200 feet.

Age of Faulting.—The Balcones faults in the vicinity of Austin, where they were mapped and described by Hill, are characteristically normal faults and where they cut the Upper Cretaceous rocks the vertical displacement is similar to that in the Mexia fault zone. However, a fault on the west side of the Balcones zone, described by Hill, in the vicinity of Austin, which cuts the Lower Cretaceous rocks, has a vertical displacement of 500 feet. The greater relative displacement of these faults in the Lower Cretaceous as compared with those in the Upper Cretaceous is worthy of note. The fact that the Balcones zone is sharply bounded on the west by a fault is worthy of note for it lends weight to the theory that these faults are in rather definitely defined zones. A common origin for the faults in the Balcones and Mexia zones is suggested because they both are characterized by normal faulting with about the same displacements and the individual parallel trends. The most common trend is about N. 30° E. but there are some variations from this. According to Baker,[4] faulting is believed to have occurred along the Balcones escarpment during Pliocene or Pleistocene times. The greater displacement of the Lower Cretaceous rocks referred to above suggests that previous movement may have taken place during Lower Cretaceous time. There is some other evidence in the well records suggesting this but it is difficult with the data at hand to make definite statements regarding faulting between Lower and Upper Cretaceous time.

The faults in the Llano-Burnett Mountains as described by

[4] Baker, C. L., "Review of the Geology of Texas," *Bulletin of the University of Texas*, No. 44, page 113, 1916.

Paige have a predominate northeast trend, the fault surfaces are very nearly vertical and in some instances the vertical displacement is as much as 1,800 feet. They are definitely Pre-Cretaceous because they do not cut the overlapping Lower Cretaceous beds and they occurred after the beginning of Pennsylvanian time. It may be concluded they were produced by vertical forces, great enough to cause 1,800 feet displacements acting with compressives stresses strong enough to produce almost vertical fault surfaces. Although the individual faults of this system or zone are not closely parallel, it is significant that their general trend is northeast and is not generally divergent from the trend of the Balcones and Mexia faults. It is very likely that slipping along these faults in Cretaceous or Post-Cretaceous time would have produced faulting in any overlying rocks very similar to that now found in and along the Balcones and Mexia zones.

Competency of Beds to Transmit Stresses.—The Upper Cretaceous rocks, somewhat greater than 3,000 feet thick, are composed predominantly of shale and clays. The Austin chalk, about four hundred feet thick, is in this section but it is believed that whole series of rocks would be incapable of transmitting stresses over great horizontal distances. Vertical forces would easily break the more rigid members of this rock section and would fold and fault the less rigid and more pliant shales and clays. The Lower Cretaceous limestones and particularly the deeper metamorphic and older rocks would be more capable of trasmitting stresses over great distances. This line of evidence again suggests that the Balcones and Mexia faults are controlled by underlying structural conditions.

Primary Factors Producing Structure.—In several localities indicated on the map along the Balcones fault zone, a number of well records show that altered rocks, probably Pre-Cambrian in some cases, have been penetrated at depths much shallower than would be expected if the rocks were in their normal position.[5] These older rocks are thought to be part of the old land area Llanoria,

[5] Letter from E. M. Sellards to Jack Frost, of the Humphreys Oil Co., Dallas, Texas.

described by Miser.[6] Old land areas are areas in which folding and faulting are commonly found. This evidence, then, supports the theory that the Mexia and Balcones faults overlie older structurally deformed rocks.

Fath[7] has described the faults in North-Central Oklahoma and has advanced as a theory of origin that they are shear planes caused by horizontal slipping of buried blocks at 45° to the direction of the smaller faults. It is believed the dominant movement of the Balcones and Mexia faults has been vertical, simply a later vertical movement along buried faults, but in a number of instances detailed mapping of the Mexia faults has shown that in some cases one fault is connected with a nearby parallel fault by a short fault at an angle between 30 and 45° to them. In other cases the end of a fault will be deflected at a similar angle. These smaller faults are comparable in size to the faults described by Fath and it is likely they are caused by shearing stresses.

Concealed Fault Zones and their Effects.—The Choctaw fault in Southeastern Oklahoma has a northeastern trend for several miles northeast of its contact with the Cretaceous beds. The Cretaceous shows no evidence of faulting at this contact so the age of the Choctaw fault is Pre-Cretaceous and as Pennsylvanian beds are folded and faulted it occurred after the youngest Pennsylvanian beds found in the Ouachita Mountains. It is possible that the age of overthrusting in the Ouachita Mountains might have occurred about the same time as the normal faulting in the Llano Mountains. However, there is a broad stretch of country between the actually mapped Mexia and Balcones faults in which the structure of the rocks below the Cretaceous is unknown. The Preston Anticline in the Cretaceous rocks has a northwest trend and in Hopkins County one surface fault in Tertiary and Cretaceous rocks has been mapped with a trend approximately east and west.

[6] Miser, Hugh D., "Llanoria, the Paleozoic Land Area in Louisiana and Eastern Texas," *The American Journal of Science*, vol. 2, 5th series, Article 5, pp. 61–89, August, 1921.

[7] Fath, A. E., "The Origin of the Faults, Anticlines, and Buried 'Granite Ridge' of the Northern Part of the Mid-Continent Oil and Gas Field," U. S. Geological Survey Professional Paper 128-C, 1920.

Even though there is a belt of country between the Balcones and Mexia faults and the Choctaw which has been faulted and folded in later times with northwest trends, and although the Choctaw faulting is overthrust in type and the faulting to the south normal in type, there is a possibility that the two may have had some genetic relationship. Granting such a possibility, it supports the theory of buried faults beneath the Balcones and Mexia faults.

The convergence of several lines of evidence points to the conclusions (1) that the Mexia and Balcones fault zones are controlled by structural conditions in the underlying older rocks; (2) that these older rocks have probably been folded and faulted in a broad belt or belts across Northeastern Texas, perhaps contemporaneous with the faulting in the Llano-Burnett Mountains; (3) that later movement along the old faults has produced smaller normal faults in the overlying Upper Cretaceous rocks, which, in general, parallel the deeper faults, with occasional tendencies to shear along trends at an angle to the trends of the main faults.

After advancing the theory that the faults in the Balcones and Mexia fault zones are along a buried zone of faulted and folded rocks, one may very properly ask how this fits in with the general scheme of structure surrounding this territory. Reference to the map showing the general relationships of this territory with surrounding areas shows there are several notable features: (1) the faulted area in the Llano-Burnett Mountains to the southwest with northeast trends; (2) the Choctaw fault on the north which, at the point where it goes under the Cretaceous, has a northeast trend. This is a great overthrust representing a displacement of thousands of feet of beds. It is known that faults and folds are parallel to this fault just east of it; (3) the intervening area is unconformably covered by Cretaceous and post-Cretaceous rocks which conceal the rocks and the structure; (4) the old rocks reported in the several tests along the Balcones fault zone described above. All of these features fit in with the idea of a buried faulted and folded zone in the vicinity of the Mexia and Balcones faults. The structural trends of the Pre-Cambrian rocks in the Llano-Burnett Mountains are northwest and the major trends of the

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Arbuckles and Ouachitas are also northwest. The faulting in the Llanos cuts these older trends but in the Arbuckles and Ouachitas, Paleozoic rocks were affected by both northwest and northeast trends. The Choctaw fault, where it intersects the Cretaceous rocks, seems to be the dominant structural feature but the question as to which is the dominant trend of the buried rocks between the contact of the Choctaw fault with the Cretaceous rocks and the actually mapped surface faults in the Mexia zone make it unwise to definitely extend these trends entirely across the area. In Hopkins County one surface fault has been mapped which has a trend approximately east and west. The conclusion seems justified that the dominant structural trend of the buried rocks between the Choctaw fault on the north and the Llano-Burnett Mountains to the south is northeast, and it is likely that a faulted and folded zone extends between these two but that deviations from this dominant trend are likely between the mapped area to the south and the Cretaceous boundary to the north.

The origin of the broad structural features of this part of the country is believed to have been due to sinking of an earth segment in the Gulf of Mexico represented by the Sigsbee deep (over 2 miles below sea level), and a relative upward movement of segments in the Llano-Burnett Mountains, the Arbuckles, the Ouachitas and Sabine Uplift, and possibly other positive segments.

In summary, it is concluded that the Mexia and Balcones faults are produced by movements in a buried faulted and folded zone of underlying rocks and that this large zone is part of a folded and faulted system related, possibly, toward the north, to the Choctaw fault and its associated folds and faults and, to the south, related to a system of faulting similar to that in the Llano-Burnett Mountains, and that the great earth movements have been controlled by the negative earth segments in the Gulf of Mexico and positive segments represented by the surrounding mountains and uplifts.

Acknowledgments.—In a review of the literature in any paper treating the stratigraphy and structure of any part of Northeast Texas, it is fitting to call particular attention to certain publica-

tions. The work of Dr. Robert T. Hill has served as a background for most of the work done in this area and his report on the Black and Grand Prairies[8] deserves particular mention. In an unpublished manuscript concerning the Balcones fault zone, written by Dr. Hill, who has generously allowed the author's reference to his paper, attention is called to the fact that the first recognition of the Balcones fault was by Professor E. D. Cope,[9] who cites localities where faulting was observed in the field. Dr. Hill states that "neither Roemer (1845–1852), Marcou (1858) nor Shumard (1857–1861),[10] the earlier geologists who published on the Cretaceous of the Texas region, recognized the Balcones fault and the effect of its displacement upon the apparent sequence of the Cretaceous shales."

Although an earlier description of the faulting at Tehuacana hills, located a few miles west of Mexia and part of the Mexia fault zone, had been given by Robert T. Hill in his Black and Grand Prairies report, the first description of the now widely recognized fault at Mexia was given by Alexander Deussen.[11]

It is fitting also to recognize that in addition to the published literature this report has been made possible by a wealth of information furnished by oil companies and individuals. Several hundred well logs and detailed surface and subsurface structural maps from the files of the Humphreys Oil Company have been available for this study. Thanks are due and are extended to the colleagues of the authors and to other geologists, individuals and oil companies who have given the authors information and suggestions.

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[10] For list of papers by the authors see Bulletin 45, U. S. Geological Survey, pp. 15 and 37.

[11] U. S. Geol. Surv., Water Supply Paper 335, p. 335.

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NATIVE COPPER DEPOSITS OF THE SOUTH ATLANTIC STATES COMPARED WITH THOSE OF MICHIGAN.[1]

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INTRODUCTION.

PRODUCTION of copper in the south Atlantic States has been derived almost exclusively from sulphide ores in crystalline rocks; that from the native metal being negligible. The important commercial deposits of copper-bearing sulphide ores are confined to the crystalline rocks of either the Piedmont Upland or the Appalachian Mountain provinces extending from Maryland to Alabama, inclusive. They represent various types enclosed usually in crystalline schists partly of metamorphic igneous origin, and are genetically related to plutonic igneous masses. Native copper is not a constituent of the unaltered sulphide ore bodies below ground water level, but is frequently present as a supergene mineral in sparing quantity in the upper altered portions.

Deposits of native copper, however, in altered pre-Cambrian basic lavas of the Appalachian region have long been known and, while numerous attempts have been made to work them in Virginia and Pennsylvania, they have proved thus far to be only of slight economic importance. Much the largest and most im-

[1] Presented to the Society of Economic Geologists, Ann Arbor Meeting, December, 1922.

portant region of altered basic lavas in which the native metal is found is the "Catoctin Belt," so named by Keith,[2] and its extension southward in middle northern Virginia.

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It persists as a fairly well defined unit from middle northern Virginia through Maryland into Pennsylvania (Fig. 105). Similar occurrences in smaller areas are found in the Piedmont province of Virginia and North Carolina. The deposits present striking similarity in occurrence, structure, and mineralogic features. They were designated by Weed[3] the "Catoctin Type." Those of the Catoctin Belt especially have been the subject of investigation by many geologists, and the number of publications relating to them is fairly large, the more important ones of which are given in the list of references. In the preparation of this paper the writer has made use of these publications, supplemented by the results of his own investigations, and to their authors he makes grateful acknowledgment.

The present paper is concerned chiefly with a discussion of the geology and copper deposits of the Appalachian region of pre-Cambrian basaltic lavas, and only incidentally with the similar smaller scattered areas in the Piedmont Upland province. It summarizes the more salient features in the geology, including mode of occurrence and genesis, of the Catoctin type of copper deposit, and points out briefly the similarities and contrasts between these and the native copper deposits of Michigan.

PREVIOUS INVESTIGATIONS.

The most noteworthy detailed contribution to the geology of the region has been made by Keith[4] and to the South Mountain district in Pennsylvania and Maryland by Williams[5] and Bas-

[2] Keith, A., "Geology of the Catoctin Belt," 14th Ann. Rept., U. S. Geol. Survey, Pt. II., 1892–93, pp. 285–395.

[3] Weed, W. H., "Types of Copper Deposits in the Southern United States," *Trans. Amer. Inst. Min. Engrs.*, vol. 30, 1900, pp. 449–504.

[4] Keith, A., "Geology of the Catoctin Belt," 14th Ann. Rept., U. S. Geol. Survey, Pt. II., 1892–93, pp. 285–395.

[5] Williams, G. H., "The Volcanic Rocks of the South Mountain in Pennsylvania and Maryland," *Amer. Jour. Sci.* (3d ser.), vol. 44, 1892, pp. 482–496.

com.[6] Of special importance on the ore deposits of the Blue Ridge district in Virginia are the contributions by Weed[7] and of the South Mountain district in Pennsylvania the contribution

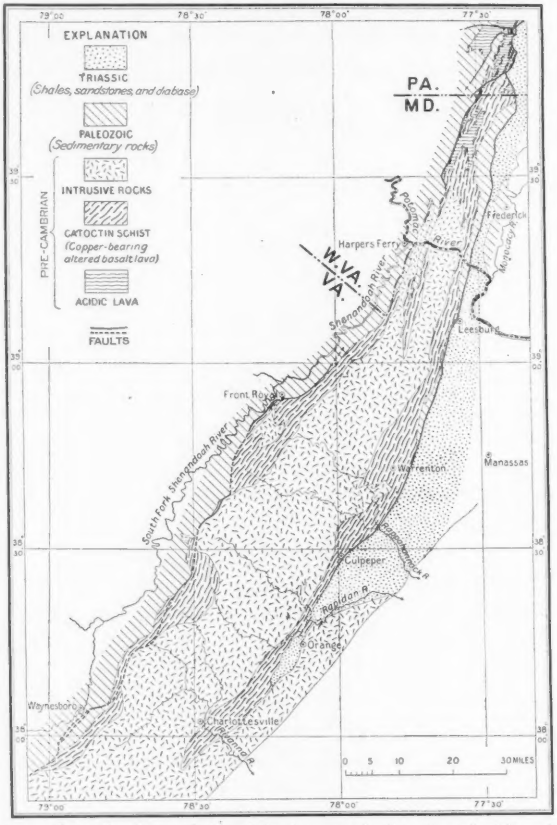

FIG. 105. Distribution of basaltic lavas of the Appalachian Region.

[6] Bascom, F., "The Ancient Volcanic Rocks of South Mountain, Pennsylvania," Bull. 136, U. S. Geol. Survey, 1896, 124 pp.

[7] Weed, W. H., "Types of Copper Deposits in the Southern United States," *Trans. Amer. Inst. Min. Engrs.*, vol. XXX., 1900, pp. 452, 498–504; "Copper Deposits of the Appalachian States," Bull. 455, U. S. Geol. Survey, 1911, pp. 11, 14–16, 93–115.

by Stose.[8] Numerous contributions by others with special reference to the ore deposits of Virginia and Pennsylvania have been published. (See List of References).

Geologic Map.—That part of the region in Maryland and northern Virginia has been mapped in detail by Keith [9] and designated by him the Catoctin Belt. South Mountain, Pennsylvania, the northern extension of the region, has been mapped by Bascom [10] and Stose,[11] and the southern part in Virginia extending southward from the southern limits of the area mapped by Keith, has been mapped by the Virginia Geological Survey,[12] but in less detail. Fig. 105, of this paper, which shows the distribution of the pre-Cambrian basaltic lavas of the Appalachian region, has been compiled from the several individual maps.

GEOLOGY OF THE BASIC LAVAS OF THE APPALACHIAN REGION.

Distribution and Geologic Relations.—The region, a mountainous one, lies between the AppalachianValley on the west and the Piedmont Upland on the east. It includes the Blue Ridge in Virginia and Maryland, and South Mountain in Maryland and Pennsylvania, and to the east of the Blue Ridge, Catoctin and Bull Run mountains in Maryland and Virginia, and their southwest extension in Virginia. Between the Blue Ridge on the west and the Catoctin-Bull Run mountains and their southwest extension on the east, is a lowland belt composed chiefly of pre-Cambrian and Cambrian crystalline rocks of both igneous and sedimentary types. Granites or quartz monzonites and their metamorphic equivalents, prevail over much of the area and, according to Keith, are in part at least younger than the basaltic lavas which have been definitely determined as pre-Cambrian (Algonkian) in age.

[8] Stose, G. W., "The Copper Deposits of South Mountain in Southern Pennsylvania," Bull. 430-B, U. S. Geol. Survey, 1910, pp. 54–63.

[9] Keith, A., *op. cit.*, 1892–93, Map, Pl. XXII.

[10] Bascom, F., *op. cit.*, 1896, Map, Pl. III.

[11] Stose, G. W., *op. cit.*, 1910, Fig. 5, p. 56.

[12] Watson, Thomas L., "Geologic Map of Virginia," Va. Geol. Survey, 1916; Stose, G. W., Miser, H. D., Katz, F. J., Hewett, D. F., Bull. XVII., Va. Geol. Survey, 1919. Map, Plate III. (in pocket).

The distribution of the basaltic lava flows is shown in Fig. 105. The westerly of the two belts is the more important one from the standpoint of copper ores. It follows essentially the crest of the Blue Ridge; the easterly one, follows the Catoctin-Bull Run mountains and their southward extension beyond Charlottesville, Virginia. These may be referred to respectively as the Blue Ridge and the Catoctin districts.

Throughout its length the region of basaltic flows is flanked on the west by the folded Cambrian and Ordovician sedimentary rocks of the Valley province. The basal bed of the sedimentary series is a quartzite deposited uncomformably on the crystalline rocks of the Blue Ridge. In the Virginia Blue Ridge district hypersthene grandiorite not older than Cambrian in age, lies between the basalt and quartzite and in places is intrusive into the former. Likewise similar intrusions of the granodiorite are exposed along the east side of the lava flows in the southern part of the Blue Ridge district in Virginia. Strong thrust faulting along the northwest slope of the Blue Ridge has complicated the relations of the Valley-Blue Ridge rocks (Fig. 105).

Triassic rocks mainly and Cambrian quartzite in places, of the Piedmont Upland, limit the lava flows on the east side of the region (see Fig. 105). Like the west or Valley side the contacts on the east side are marked in places by faults but they are of the normal type.

General Mineralogic Character.—The basaltic lava shows marked differences in structure and composition but is sufficiently uniform in general appearance to be always readily identified. It corresponds closely in mineral composition and texture to diabase, and even in the completely schistose phases of the rock diabasic texture is usually discernible in thin sections. It is normally a dense, heavy, dark bluish green rock when fresh, becoming lighter yellowish green with increase of epidote. Both massive and schistose phases are common, the former being especially frequent in the Virginia portion of the region, but probably somewhat less frequent in the South Mountain, Pennsylvania, district. The rock is aptly described as greenstone.

The pyroxenic constituent is augite. Hypersthene, a common mineral in many of the Triassic diabases and other igneous rocks of the Virginia Blue Ridge has not been identified. Olivine and subordinate hornblende are sometimes present in the less altered massive rock. The remaining constituents, plagioclase feldspar and magnetite, show the usual characters for such rocks. The most striking feature in the composition of the lavas at present is the extensive development of chlorite and epidote through chemical metamorphism of the principal minerals, pyroxene and plagioclase. These (chlorite and epidote) are the principal minerals in the more schistose rock, without trace of the original augite, olivine, and hornblende, but plagioclase and magnetite are usually shown. Much of the magnetite, usually present in quantity, has largely or completely altered to leucoxene. Quartz as eyes and small stringers or lenses, and often intergrown with epidote as epidosite, and in places of the Blue Ridge of Virginia in the rock type unakite, is a common accompaniment of the more highly epidotized portions of the rock.

Chemical Composition.—Chemical analyses of the basalt are given in the table below, with which are included analyses of the Triassic diabase and the Blue Ridge hypersthene granodiorite of Virginia for comparison.

Attention is called in the analyses to the percentage amounts of ferrous and ferric oxides. Nos. I. and II., in which the copper occurs, are not only rich in iron but are high in *ferric* iron as compared with other rocks of the region. The high *ferric* iron has resulted from the regional metamorphism of the basic lava and not from the solutions that deposited the copper, although the solutions naturally followed the sheared zones. Although chemical analyses are partly lacking, field and microscopic evidence indicate that the sheared zones are rich in ferric iron but may or may not contain copper. In other words it is believed that the formation of ferric iron was independent of the copper mineralization, but that the latter was closely associated with areas rich in ferric iron as epidote.

TABLE I.

ANALYSES OF GREENSTONE (CATOCTIN) SCHIST, DIABASE, AND GRANODIORITE FROM VIRGINIA.

	I	II	III	IV	V	VI
SiO_2	50.28	51.97	51.13	50.63	63.76	65.30
Al_2O_3	10.62	12.27	11.45	18.16	13.04	13.96
Fe_2O_3	9.04	5.01	7.03	1.44	1.36	1.14
FeO	6.48	9.21	7.85	9.32	5.64	4.98
MgO	4.17	5.07	4.62	5.23	1.37	1.10
CaO	9.76	6.55	8.16	11.14	4.30	3.78
Na_2O	2.67	3.84	3.25	1.83	2.36	3.12
K_2O	.49	.51	.50	.51	3.76	3.52
H_2O-		.08	2.69	.23	.10	.13
H_2O+	2.90	2.41	2.85	.60	.14	.39
TiO_2	2.96	2.75	.21	.90	2.85	2.13
P_2O_5	.12	.31	.28	.13	.88	.61
MnO	.23	.33	.15	.19	.19	.20
CO_2	.31	trace	.....	.....	.....	.....
S	.....	.03	.01	.....	.06	.03
	100.03	100.34	100.18	100.31	99.81	100.39

I. Greenstone (Catoctin) schist (altered basalt) west of Afton on east slope of the Blue Ridge in Rockfish Gap, Nelson County, Virginia. Penniman and Browne, analysts.

II. Massive Catoctin schist (altered basalt) 1½ miles west of Carter's Bridge, Albermarle County, Virginia. Lee and Wight, analysts.

III. Average of I. and II.

IV. Average of ten analyses of Triassic diabases from different localities in the Piedmont Upland province of Virginia.

V. Hypersthene granodiorite from the northwest slope of the Blue Ridge Mountains near the boundary between Madison and Green counties, Virginia. J. G. Dinwiddie, analyst.

VI. Average of five analyses of hypersthene granodiorite from different localities in the Blue Ridge Mountains, Virginia.

Physical Characters.—Two flows of the basic lavas, an upper and a lower sheet, were recognized by Keith,[13] separated by an erosion interval of considerable length during which flows of andesite and rhyolite and intrusions of granite were initiated. They represent accumulations from fissure eruptions poured out onto a land surface. Evidence is lacking of interbedded sediments, such as conglomerates, which characterize the Michigan copper district.

[13] Keith, A., *op. cit.*, 1892–93.

The flows have suffered much erosion. Their total thickness is unknown but it is undoubtedly great. They are frequently marked by amygdaloidal tops. Absence of zeolitic minerals as fillings is noteworthy, although some observers mention them in the South Mountain district. Where observed by the writer the fillings are composed of epidote and quartz, and sometimes pink feldspar and calcite, or a combination of these. So far as the writer's observations extend neither native copper nor its compounds have been noted in association with the minerals composing the amygdules. Jasper in small and large masses is noted in places in the Blue Ridge district of Virginia. Red color of the lava tops, present in the Michigan region and due, according to Graton and associates of the Geological Department of the Calumet and Hecla Mining Co.,[14] to the presence of ferric iron in the form of hematite, has not been observed in the Appalachian lavas. Change of color due usually to the development of an excess of epidote is quite characteristic, and for such parts of the lava flows would probably show on analysis an excess of ferric over ferrous iron, the ratio of which for other parts of the flows would be reversed. It seems most probable that there is a genetic relationship of the copper to epidotization, since the native metal is usually found in the more highly epidotized portions of the lavas.

Associated Igneous Rocks.—In the northern part of the region, especially in South Mountain, the basic lavas are intimately associated with acidic lavas of rhyolitic composition. The latter have but slight development in the Virginia portion of the region.

Of the two types of associated lavas the acidic or rhyolitic type is regarded by Bascom, Stose, and others, as the older although as stated in the report by Mr. Stose he formerly regarded the acidic lava as the younger. It is noteworthy that in the South Mountain district as mapped by Bascom and Stose; the copper mines and prospects are located near the contact of the basic and acidic lavas but nearly always within the basic type.

[14] Ann Arbor Meeting of the Society of Economic Geologists, December, 1922.

According to Stose [15] several of the openings are located in the acidic lava.

Hypersthene granodiorite [16] is abundant along the western margin of the Blue Ridge district in Virginia, and also along the eastern margin farther south.

The granites of the eastern side (see Fig. 105) are of several mineralogic types, the principal one of of which is biotite-bearing with blue quartz, the latter being characteristic of many of the Virginia Blue Ridge quartz-bearing intrusives. From its intricate fingering relation to the basaltic lavas Keith [17] regards the granite as intrusive in the lavas and therefore younger, but pre-Cambrian in age.

Plutonic intrusive rocks are unknown in the northern portion of the region.

STRUCTURE.

Throughout its entire extent the region is one of strong folding and faulting. The Blue Ridge, South Mountain, Catoctin, and Bull Run mountains mark the principal lines of folding and faulting. They are also the areas of distribution of the basic lavas with which the copper is associated. Profound thrust faults limit the region on the west side and normal faults on the east side.

The thrust faults have variable but generally gentle dips to the southeast, with minimum throw in case of some of the Blue Ridge faults of four or five miles. Structure sections prepared by Keith [18] across the trend of the structures show the larger structural features of the region. Minor faulting and folding occur, but are less easy to recognize and trace.

Jointing is a prominent structural feature of the basic lava. The planes are often closely spaced forming zones of vertical sheeting along which the ores are chiefly segregated and the rock

[15] Stose, G. W., *op. cit.*, 1910.

[16] Watson, T. L., and Cline, J. H., "Hypersthene Syenite and Related Rocks of the Blue Ridge Region, Virginia," *Bull. Geol. Soc. Amer.*, 1916, vol. 27, pp. 193–234.

[17] Keith, A., *op. cit.*, 1892–93.

[18] U. S. Geol. Surv. Fourteenth Annual Report.

most strongly epidotized, accompanied at times by veinlets of white crystalline quartz and, in places, similar bodies of epidosite.

METAMORPHISM.

Regional and chemical metamorphism of the basic lavas are pronounced and widespread. Evidence of the former is shown in strongly developed schistose structure; the latter in extensive development of epidote and chlorite, and in places quartz and some asbestiform serpentine. It is in such altered portions of the rock that the ores are chiefly found, and the copper occurs in places in intimate association with each of these minerals, but most frequently with epidote.

The metamorphism of the lavas (which were surface flows) was accomplished at depth beneath a cover of Cambrian and possibly younger sedimentary rocks. Later, the lavas were re-exposed at the surface by erosion and removal of the overlying sediments.

Volcanic activity, in the form of thin sheets of basaltic lava, recurred in the early part of the Cambrian, as evidenced by interbedded lava flows and sediments at a number of localities along the west side of the Blue Ridge south of the region of pre-Cambrian (Algonkian) lava flows in Virginia,[19] and extending into Tennessee.[20] These Cambrian lavas are also generally more or less altered. Copper thus far has not been found in them.

Changes in mineralogic composition of the pre-Cambrian basic lavas, the result of interaction of the original minerals, are the most noticeable feature of the rock. Macroscopically it is evidenced chiefly in a change of color to dark green and lighter yellowish green. Chlorite and epidote have developed on an extensive scale, so that thin sections of the rock often show not even a trace of the original mafic minerals, and sometimes, though to a less degree, the plagioclase is destroyed. White

[19] Watson, Thomas L., and Cline, J. H., "Extrusive Basalt of Cambrian Age in the Blue Ridge of Virginia," *Amer. Jour. Sci.*, vol. XXXIX., 1915, pp. 665–669.

[20] Jenkins, O. P., "Mineral Resources of Tennessee," Tenn. Geol. Survey, vol. 6, No. 2, pp. 67–68, 1916.

crystalline quartz as veinlets is a frequent associate in the more strongly epidotized portions of the rock. Quartz is often intergrown with the epidote in the rock epidosite. To a less extent asbestiform serpentine has formed.

Epidote, formed as an abundant secondary constituent of the altered basic lavas, is probably the most frequent mineral developed as amygdaloidal fillings. The epidote amygdules were doubtless formed in advance of the metamorphism which resulted in the widespread epidotization of the rock. Moreover the two classes of epidote were differently formed. Copper has not been observed in association with the epidote filling amygdules, but is most intimately associated with the epidote of the more highly epidotized portions of the rock, hence it seems probable that the formation of epidote is genetically connected with that of the native metal.

The widespread epidotization resulting largely from regional metamorphism, is localized along zones of jointing and shearing where the waters naturally circulated more freely. Along such zones the copper is largely concentrated. The more strongly epidotized areas usually fade macroscopically into the basalt, but microscopically some epidote is usually present throughout the rock. Some observers record decrease and fading out of epidote with depth in some of the deeper mine openings.

ORE DEPOSITS.

Mineralogical Character and Occurrence.—Native copper is the chief ore mineral. Associated with it are usually cuprite, some bornite and chalcopyrite, and occasionally a little chalcocite. Bornite is probably in excess of chalcopyrite. Malachite and azurite are nearly constant oxidation products as stains in the surface rock and as films and coatings on joint and fracture surfaces of the rock. Chrysocolla is of sparing occurrence. Cuprite is also secondary after the native metal which sometimes forms nucleal masses surrounded by the oxide. Masses of the native metal weighing several pounds have been reported but are exceptional.

The copper minerals do not occur in well-defined veins but as disseminations in the more strongly epidotized portions of the basic rock, including quartz veinlets and similar bodies of epidosite, and along crevices and joint planes. Bright glistening grains and masses of native metal are frequent in the veinlets of glassy quartz and epidosite, and sometimes in serpentine admixed with the quartz. The quartz veinlets, however, are not always copper-bearing. So far as mining operations have extended, the claim has been made by some that the amount of copper decreases with depth, the bulk of the ore being largely confined within 50 or 60 feet of the surface.

The ores are usually found in the altered pre-Cambrian basalt though several occurrences have been noted in the underlying rhyolitic lavas of South Mountain, Pennsylvania, apparently at fault contacts. Throughout the region the ores are strikingly similar in mode of occurrence and mineral associations. As amygdule fillings they have thus far been found only sparingly in the South Mountain district of Pennsylvania. Several occurrences of the metal in the Blue Ridge district of northern Virginia, are in apparent breccia zones. Veinlets of quartz and epidosite with which copper is intimately associated are often developed in the more strongly epidotized rock. Asbestiform serpentine, calcite, and pink feldspar, named in order of abundance, are in association with the copper minerals in places Jasper sometimes occurs. Small bunches of black tourmaline and specular hematite have been noted in some of the Virginia occurrences. Hematite is also reported in the South Mountain district as occurring sparingly in association with vein quartz and with some of the amygdule fillings. Of the above nonmetallic minerals associated with the copper, epidote, quartz, and chlorite are the commonest and are almost constantly present. These are followed by serpentine, calcite, and pink feldspar, the latter being the least common of the three.

Mining Developments.—The copper ores have attracted attention for almost a century and numerous attempts have been made to work them in Virginia and Pennsylvania, but thus far with

only slight success. They have been developed by shafts to a maximum depth of about 300 feet in Virginia and to a less depth in Pennsylvania. In the latter State, however, copper was reported to a depth of 600 feet in a bore hole. This would indicate that for this locality at least the copper is not limited as believed by some to a shallow surface zone of 50 or 60 feet depth.

GENESIS OF THE ORE.

That the concentration of the copper in its present form in the more epidotized portions of the basalt is secondary, is generally conceded. Whence the source of the copper and how it was formed as now segregated are two important questions.

Based on the geology of the region three possible sources of the metal may be considered. These are: (1) Original in the basalt itself, (2) introduced from below by deep-seated magmas, and (3) introduced by Triassic diabase. Of these the third is the least likely and in the writer's opinion entirely improbable. It is again referred to later.

(1) It is generally agreed that the source of the metal was in the basalt and not from the outside. Also that the copper as an original constituent of the basalt existed not as native metal but probably as sulphide, chalcopyrite chiefly. Copper-bearing sulphides not associated with the native metal have been noted in places as minute particles in the least altered portions of the lavas.

Concentration of the Virginia deposits is, according to Weed, the result of downward percolating surface waters. He says:[21] "Where the joints are locally concentrated a natural path is afforded for downward-moving superficial waters, which have produced the ore deposits, and it is along such paths that the greatest alteration should be expected. . . . Accordingly it should be expected that the richest ore would be found near the surface, for it is in the most superficial belts that the solvent power of atmospheric waters is strongest and that the ore would be found steadily to diminish in depth."

[21] Weed, W. H., "Copper Deposits of the Appalachian States," Bull. 455, U. S. Geol. Survey, 1911, p. 114.

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For the similar deposits of South Mountain, Pensylvania, Stose has reached a different conclusion. He says:[22] "The massive layers of copper-bearing epidote and small blebs of epidote and quartz in the center of relatively fresh rock are undoubtedly the result of deeper-seated alteration, under the influence probably of heated water, and it is concluded that most if not all the concentrated copper in the South Mountain district was deposited in this manner. As the metamorphism of these rocks and the production of most of the epidote occurred in pre-Cambrian time, the concentration of the copper in its present position and form must also have taken place at that time."

The conception of the ore genesis from downward moving superficial waters is based on the character of the ore, its supposed occurrence within a limited shallow depth below the surface, and its concentrations localized principally along zones of shearing and sheeting in the more strongly epidotized portions of the rock. It is the opinion of the writer that in the absence of a sufficient number of deep openings over the copper-bearing region, the view so strongly emphasized by some that the ores are confined to a surface zone of slight depth, is inconclusive.

Concentration of the copper in its present position and form is undoubtedly connected with the epidotization of the basaltic rock along such structural positions as mentioned above. Weed and others, including the writer, concluded that for the Virginia Blue Ridge district, the areas of strong epidotization with which the copper is associated were the result of downward moving atmospheric waters. Stose on the other hand concluded that for the South Mountain district the epidotization resulted from the action of deeper seated heated waters, mainly during pre-Cambrian time. As further pointed out by Stose the basic lavas of the Appalachian region were subjected to great compression and heat during pre-Cambrian time and again late in the Carboniferous, so that alteration of the original minerals must have taken place in the presence of heated waters. Moreover it seems

[22] Stose, G. W., "The Copper Deposits of South Mountain in Southern Pennsylvania," Bull. 430-B, U. S. Geol. Survey, 1910, pp. 62–63.

probable that extraction of the copper from the basaltic rock followed fairly closely upon consolidation of the lava. This would bring the period of both epidotization and metallization principally within pre-Cambrian time.

Metallic copper, the most important ore mineral in the region, was probably precipitated from sulphide solutions which entered the more highly epidotized portions of the rock along sheared zones rich in ferric iron as epidote. Ferric iron oxidized the sulphur of the solutions and deposited the copper as native metal, the chemical reaction being similar to that postulated for the Lake Superior region by Graton and his associates[23] of the Geological Department of the Calumet and Hecla Mining Company, by Steinmann,[24] Singewald and Berry[25] for Corocoro, by Bateman[26] for Connecticut, and by Lewis[27] for New Jersey.

Free ferric oxide in the form of hematite, an important constituent in the lava tops in the Michigan copper region, occurs only sparingly in the Appalachian lavas. Magnetite is usually present as a subordinate mineral. As pointed out elsewhere in this paper, iron-bearing silicate minerals are the dominant constituents of the altered basic lavas (Catoctin schist). Of these epidote is vastly the most abundant silicate mineral present in the copper-rich as well as the ferric iron-rich portions of the rock, and it is always intimately associated with the metal. The two, epidote and native copper, were probably formed at about the same time. It seems probable, therefore, that ferric iron in the epidote was the principal precipitating agent involved in the for-

[23] Ann Arbor Meeting of the Society of Economic Geologists, December, 1922.

[24] Steinmann, G., "Die Entstehung der Kupfererzlagerstätte von Corocoro und verwandter Vorkommisse in Bolivia," Festschrift, Harry Rosenbusch, 1906, pp. 335–368; "El Origen de los Yacimientos Cupriferos de Corocoro y de Otros Semejantes en Bolivia," *Revista Minera*, Oruro, Sept., 1916.

[25] Singewald, J. T., and Berry, E. W., "The Geology of the Corocoro Copper District of Bolivia," The Johns Hopkins University Studies in Geology, No. 1, 1922, 117 pp.

[26] Bateman, Alan M., "Primary Chalcocite: Bristol Copper Mine, Connecticut," ECON. GEOLOGY, vol. XVIII., 1923, pp. 122–166.

[27] Lewis, J. Volney, Ann Arbor Meeting of the Society of Economic Geologists, December, 1922.

mation of the native copper in the Appalachian pre-Cambrian basic lavas.

(2) A second possible source of the copper which merits consideration is from outside the basic flows in deep-seated intrusive magmas. Attention has already been directed to the occurrence of hypersthene granodiorite along the west side of the Appalachian lavas and in places along the east side also, in the Blue Ridge district of Virginia. The granodiorite intrudes the lavas in places along the west side, and is therefore younger. Furthermore concentrations of copper are found near the contacts of the basic lava and granodiorite, but the character of ore and associated minerals is not different from that of the deposits found throughout the region of basic lava flows remote from visible bodies of intrusive rock.

As elsewhere, strong development of epidote is a characteristic feature both in the lava flows and in places in the granodiorite, forming in the latter case the rock-type unakite. In one or two places removed from visible contacts of the intrusive rock, small bunches of black tourmaline are associated with the copper. The common mineral associations of the deposits, however, are not characteristic of ascending thermal waters, especially those rich in carbon dioxide, which might have followed the intrusion of the granodiorite for as Lindgren[28] remarks, it seems unlikely that the abundant epidote always present with the copper would form under such influences.

Native copper in deposits of the Catoctin type occurs in places in the Piedmont province of Virginia and North Carolina. The type is represented in places in the Virgilina district[29] of Virginia and North Carolina, where the metal apparently shows preference for quartz rather than for epidote. The metal there is regarded as a hypogene mineral formed from ascending thermal waters.

(3) Although dikes of Triassic diabase occur sparingly west of the Blue Ridge in the Valley region and occasionally in the Blue Ridge, indications are that the principal areas of Triassic

[28] Lindgren, W., "Mineral Deposits," 2d edition, 1919, p. 443.

[29] Laney, F. B. The Geology and Ore Deposits of the Virgilina District of Virginia and North Carolina, Va. Geol. Survey, Bull. XIV, 1917, pp. 78–79.

rocks which limit the Catoctin schist on the east, including igneous sheets and dikes, probably never had a much greater extension westward than at present. There is certainly no evidence that areas of Triassic sediments and associated diabase ever extended as far west as the main Blue Ridge in Virginia.

Along the western margin of the main belt of Triassic rocks are exposed in many places, especially in Virginia, basal Triassic conglomerate beds which establish the position of the shore line along the western margin of the Triassic trough. Of especial importance is the occurrence over a part of the Virginia area of basal Triassic conglomerate composed of boulders of varying size and degree of wear of the copper-bearing pre-Cambrian basalt from immediately to the west (see Fig. 105). These boulders are sometimes copper stained, indicating that the copper was present in them prior to their erosion and deposition in Triassic time.

Résumé.—Present available information leads the writer to the view that the source of the copper in the Appalachian region was in the pre-Cambrian basic lavas. It probably originally existed in the lavas in the form of sulphide, and was concentrated as native metal in its present position by hot circulating waters coextensive with the epidotization and the formation of quartz veinlets, under the oxidizing influence of ferric iron in the epidote. More specifically the native copper probably resulted from sulphide solutions entering the rocks rich in ferric iron as epidote along zones of shearing and sheeting, that oxidized the sulphur of the solutions and deposited the copper as native metal. Further, that the principal period of formation of the metal was pre-Cambrian.

This is at variance with the view held by Weed and others that the richer deposits of the metal represent recent concentrations derived from the lavas through the action of downward percolating surface waters.

The associated metallic oxide and carbonates are the surficial derivatives of the native metal and probably to some extent the sulphides.

Until further careful detailed field work has been accomplished, the writer does not feel that the possible source of the metal from deep-seated intrusive magmas has been definitely elimated.

COMPARED WITH THE MICHIGAN NATIVE COPPER DEPOSITS.

The following similarities and contrasts between the Catoctin type of the Appalachian native copper deposits and the native copper deposits of Michigan are briefly summarized:

Similarities:

(1) Containing rocks are basic lava flows of basaltic type and pre-Cambrian age—Keweenawan in the Lake region and Algonkian in the Appalachian region. Present total thickness of the lava flows is vastly greater for the Lake region.

(2) Lava flows show amygdaloidal tops which are prominent and of great persistance in the Lake region, and which yield the bulk of the copper produced from the lavas though the largest deposits are in felsite conglomerate. They are less prominant in the Appalachian region.

(3) Associated with the copper-bearing basic lavas are those of acidic character; also either directly or indirectly in places deep-seated intrusive rocks.

(4) Unconformable Cambrian sediments, especially sandstones or quartzites, often in faulted contact with the lavas.

(5) Principal ore mineral is native copper.

Contrasts:

(1) Lake Superior deposits are of vast commercial importance, those of the Appalachian region not yet proved to be of economic value.

(2) Zeolitic minerals are essentially absent as amygdaloidal fillings in the Appalachian region, and native metal rarely occurs with the amygdaloidal minerals of the kinds previously mentioned.

(3) Absence of interbedded sediments, especially conglomerates, in the Appalachian region, which have proved

in the Lake Superior region to be commercially important ore bearers.

(4) Greater metamorphism of the Appalachian lavas, manifested in widespread schistose structure and development of epidote and chlorite accompanied by veinlets of quartz and epidosite, and in places some asbestiform serpentine.

(5) Essential absence of hematite as a constituent in the amygdaloidal tops of the Appalachian region, and the widespread greater development of epidote.

(6) Genesis of the ore. In the Appalachian region the present information points to the belief that the source of the metal was within the basic lavas, derived from copper compounds, probably sulphide, sparingly disseminated through the basic rock and concentrated in its present form and position through the agency of heated waters. The deposits usually occur in the highly epidotized portions of the rock rich in ferric iron, developed along zones of shearing and sheeting. Probably ferric iron in the epidote was the principal agent involved in the precipitation of the metal by oxidation of the copper solutions. Veins, which form one of the modes of occurrence of the metal in the Lake superior region, do not occur. Neither is there evidence of metasomatic replacement as a process in the ore formation.

In the Lake Superior region the source of the metal until recently was generally regarded as being in the lavas, and concentrated in its present form and position according to some by descending waters, to others by ascending thermal waters. It is believed by Graton and associates [30] that the source of the metal was from deep-seated magmas, that the solutions were sulphide solutions, that they were oxidized by ferric oxide, and thus produced native copper by oxidation of the copper solutions.

[30] Ann Arbor Meeting of the Society of Economic Geologists, December, 1922.

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GEOLOGY OF THE PEARL LAKE AREA, PORCUPINE DISTRICT, ONTARIO.[1]

H. S. ROBINSON.

THE gross production of the Porcupine District, up to the end of 1922, has amounted to nearly $103,000,000, and the yearly production has shown a steady increase.[2] This has been due, not to the increase of the number of producing mines, but to the exploitation of numerous large ore bodies in the three mines which account for nearly all of the gold produced in the district. The success of the Hollinger, Dome, and McIntyre mines, and the probability that none of them have reached the peak of their productivity even at their present great rate, has attracted considerable notice to these mines and has stimulated exploration in their vicinity. The nature of the ore bodies has been eagerly studied in the effort to locate similar conditions on neighboring properties.

The mines of the Pearl Lake area account for over 80 per cent. of the total production of the Porcupine camp. The ore bodies so far exploited are similar in grade, mineralogical composition and structural character, and occur in the same formations, so that the writer ventures to describe the area as a unit, though most of the data presented is the result of work at the McIntyre mine. There are two producing mines at present, the Hollinger Consolidated Gold Mines, Ltd., and the McIntyre-Porcupine Gold Mines, Ltd., several properties have produced considerable gold in the past and there are a number under development. The statistical data below presents this:

[1] Presented at New York Meeting, Society of Economic Geologists, May, 1923.

[2] For a general article on the Porcupine District see Ontario Gold Deposits, Percy E. Hopkins, Vol. XXX., Part 2, Ont. Dept. of Mines.

Mine	Approximate Gross Production	1922 Production	Remarks
Hollinger	63,000,000	12,274,114	4000 tons per day
McIntyre	15,000,000	1,937,105	850 tons per day
Porc. Crown	2,800,000	.....	Closed down
Vipond	800,000	.....	Developing
Schumacher	500,000	.....	Sold to Hollinger
Newray	150,000	.....	Developing
Plenaurum	50,000	.....	Closed down
Goldale, Rochester and Holtyrex			Developing

GENERAL GEOLOGY.

The formations present in the Pearl Lake area in order of succession are:

Pleistocene
- Glacial and Recent.....Sand, gravel, glacial debris

Pre-Cambrian
- Keweenawan.....Diabase dikes
- Algoman.....Quartz porphyry
- Keewatin.....Basic extrusives

The Nature of the Keewatin.—In the early reports on the district, it was noted that bands of ellipsoidal and amygdaloidal lavas were traceable over considerable distances, but no further classification of the Keewatin was made, except that the general extrusive nature of the rocks was pointed out.[3] Similar formations were observed in other parts of northern Ontario and, in 1919, the discovery of a series of Keewatin lava flows in Halloway Township was described in a report by the Provincial Geologists.[4] These rocks had been tilted on edge but otherwise they were remarkably well preserved. They afforded unusually clear examples of basaltic lava flow textures. The significance of the textures of the altered lavas of other districts was at once apparent and was pointed out. This led to a resurvey of the Porcupine District by A. G. Burrows in the summer of 1922.

[3] A. G. Burrows, The Porcupine Gold District, 24th Ann. Report, Ont. Bureau of Mines.

[4] Abitibi-Night Hawk Lake Gold Area, 28th Ann. Report, Ont. Bureau of Mines.

In spite of the difficulties arising from superficial glacial and soil covering and the obliteration of original texture by dynamic metamorphism and later intrusion, a number of individual flows were mapped. The structure of the Keewatin was revealed as a broad easternly-pitching synclinorum. Meanwhile the writer had mapped several flows underground and found some remarkable relationships between Keewatin structure, porphyry intrusion and the location of veins.

The original composition of the Keewatin varied from dacite to olivine-free basalt. The more basic types were probably non-porphyritic rocks composed of equal parts of augite and calcic-plagioclase with considerable titaniferous magnetite. The more acid types commonly show quartz phenocrysts and traces of feldspar phenocrysts. Small areas of leucoxene represent former phenocrysts of some ferro-magnesium mineral. The ground-mass was evidently predominately feldspar with minor augite. The original minerals are now almost completely destroyed, the recrystallized rocks being aggregates of quartz, carbonates, chlorite, sericite and leucoxene, with traces of original texture. Most of this alteration is the result of dynamic metamorphism and, locally, contact metamorphism, but it is possible that some of the alteration took place at the time of the extrusion of the lavas, promoted by hot, mineralized, descending surface waters.[5] The flows are extensive, laterally suggesting extrusion of the fissure type. One spherulitic flow can be traced almost continuously from the north limb of the syncline at the Newray mine to the south limb at the Apex mine, a distance of 4 miles. A typical cross-section of a flow consists of a chilled base, usually only a foot or so thick, a medium- to coarse-grained interior of diabasic or gabbroid texture, making up 75 per cent. of the total thickness of the sheet, a narrow belt of fine-grained, densely amygdaloidal lava near the top and a crust of fragmental. scoriaceous, or tuffaceous material. Sometimes the interior of the flow is composed of pillow lava. Pillow (ellipsoidal) lava

[5] For analyses see report on Porcupine Gold District (loc. cit.) and Igneous Rocks and their Origin by R. A. Daly, p. 27.

may be due to subaqueous extrusion, but the occurrence of both pillow and normal texture along the strike of the same flow lends some doubt to this possibility. Ellipsoidal, spherulitic, and amygdaloidal textures are commonly associated with basaltic lavas and the general occurrence of these textures in the Porcupine area led to the application of the name basalt to the Keewatin rocks there, although it was soon recognized that more acid types existed.

Keewatin Deformation Prior to Porphyry Intrusion.—The Keewatin lava extrusions attained a tremendous thickness. The series is standing on end and may be traversed for a distance of 20 miles normal to the strike with the tops of the flows facing north, before the reverse position is encountered. The extrusion of the basalts was accompanied by settling of the Porcupine basin. This subsidence continued throughout the Temiskaming Era, during which time a series of conglomerates and slates was deposited in the eastern end of the basin. There is a distinct but moderate unconformity between the Keewatin and Temiskaming series, the Keewatin lava flows dipping 20 to 30 degrees unconformably to the bedding planes of the sediments.[6] Subsidence and regional compression formed a series of folds striking a little north of east and pitching to the east. The general structure of the Porcupine area is a large eastwardly-pitching synclinorum with minor folds.

All of the Keewatin was rendered slightly schistose so that even in the more massive types the general direction of schistosity is easily recognized. Deformation however was differential. The weaker members of the series, such as the fragmental flow tops and the more heterogenous pillow lavas, were less resistant than the coarse-grained centers of flows and are usually more schistose. Certain parts of the Porcupine syncline developed lines of weakness, so that long continuous belts of schist can be traced parallel to the axis of folding. One such belt traverses Pearl Lake, striking about N. 70° E. Its width is about 1,200 ft., and with few exceptions it embraces all of the important veins of the Pearl Lake area.

[6] Private communication. D. G. R. Wright, So. Porcupine, Ont.

This describes the condition of the basalts, except where they have been further altered by the intrusion of the porphyry. Northeast of Pearl Lake on the Goldale, Armstrong-Booth, and Newray they are standing nearly vertical with the fragmental tops facing south. The contacts swing in a broad arc to the southwest. Only a few fragments of the original contacts can be found on the western end of the syncline, but such as are found show broad areas of fragmental material with flat dips to the east. On the south side of the syncline the strikes are east and the dips vertical, but the tops of the flows are facing north. Contacts at the west end are more obscured by metamorphism and probably flat dips, close folding, and cross-folding complicate the problem.

The identification of flow tops is not always easily made, even where there is no superficial covering. Differential weathering brings out the texture of the fragmental tops very clearly. The smooth surface of a wet diamond drill core is also a convenient means of recognizing texture, but care must be used to check results in several parallel drill holes as a small section of brecciated rock or of pillow lava resembles tuffaceous material. The only safe criterion is to identify the several phases of a flow in their proper order, namely, the chilled base, coarse interior, amygdaloidal top and tuffaceous crust.

Intrusion of the Porphyry.—The intrusion of the quartz porphyry was the last phase of the tectonic phenomena which began with the subsidence and folding of the Keewatin and Temiskaming formations. A large mass came up in the center of the Porcupine basin, where there was a minor anticline, as indicated by a sharp roll in the flow contacts. Another large mass occupies the area south-west of the Porcupine Crown mine, with its eastern edge parallel to the strike of the flows at that point and its eastern face parallel to the bedding planes of the flows. Several smaller masses came up along the flanks of the major syncline and outcrop in lenticular areas, conforming to the strike of the flows, to the bedding of the Temiskaming sediments, or to the contact of the Keewatin and the Temiskaming. Several

masses occur in the vicinity of Pearl and Gillies Lakes, having been intruded roughly along the bedding planes of the northern flank of the major syncline. All of the porphyry masses exposed by mining operations show an eastward pitch, conforming to the pitch of the Keewatin trough. It is evident that the structure of the Keewatin determined the direction of intrusion.

Nature of the Porphyry.—The porphyry is a light grayish rock in which quartz phenocrysts up to 2 mm. in diameter are readily distinguished. The feldspar phenocrysts, of acid plagioclase, are not so easily seen, except where weathering has brought them out. The rock occurs in both massive and schistose phases. Where strongly schistose the feldspars are almost completely altered. The more basic types show elongated patches of leucoxene which probably are the last traces of hornblende. The groundmass is composed of quartz, feldspar and chlorite.[7]

The mass of Porphyry which underlies Pearl Lake and extends about 1,500 ft. to the west of the western end of the Lake has been well outlined by mining operations to a depth of 2,000 ft. Its maximum length is 4,300 ft. and its greatest width 1,400 ft. It tapers to a point at both ends. It is strongly schistose, somewhat more so than any other stock observed in the district. The north and south walls dip slightly to the south and the stock pitches to the east at an angle of 50 degrees. The horizontal section of the Pearl Lake porphyry shows a peculiar and significant outline. While the north and south boundaries have smooth walls, with few apophyses, the east and west ends are extremely jagged and irregular. Long apophyses extend out from the main mass. The intruded rocks opposed penetration in the north and south direction but in the east and west direction, in the strike of the Keewatin lavas, there was less resistance. Where these apophyses penetrated the older rocks there is evidence of the extreme mobility of the magma and of its ability to freeze with coarsely crystalline texture even at the remotest points. There is no evidence of great heat at the contacts. The mobility of the intrusive at moderate temperatures and the tendency to

[7] For analyses see Burrows, A. G., *Loc. cit.*

coarse crystallization suggests richness in magmatic water. In a few places in the Pearl Lake area and elsewhere in the district, the schist at the margins of the porphyry has been intruded by a swarm of pipe-like apophyses, oval in cross-section. This mode of intrusion has been described by A. R. Whitman [8] and named by him Ecolé Injection. The injected pipes range in diameter from one inch upwards. They decrease in number as one goes away from the porphyry contact. They are oriented in the direction of the schistosity and are more elongated as the schistosity is more pronounced. An examination of the injected particles shows them to be almost identical with the parent magma. They are not schistose as is the intruded rock. The texture of the smallest particles is coarsely crystalline and the mineralogical character indicates that they were rich in mineralizers, especially water. There is a greater development of sericite, some microperthite and tourmaline. The quartz and feldspar phenocrysts are cracked and torn asunder by the final movements of the viscous groundmass.

All of the porphyry masses show similar modes of intrusion. The contact phenomena and the end phases of intrusion and differentiation, such as vein formation, are similar throughout the district. This points to a common source for the different stocks and to contemporaneous intrusion. Other facts suggest that the stocks are extensive apophyses from a parent magma. The various stocks show slight but characteristic variations in composition, notably in the degree of schistosity, in the proportion of quartz to feldspar phenocrysts, and the amount of secondary minerals. Mining operations show that the horizontal section of most of the stocks, as shown at the surface, is remarkably constant to the deepest levels, allowing for the eastward pitch. There does not seem to be any tendency for the individual stocks to coalesce at moderate depths. The stocks are, therefore, far enough removed from the parent magma to show divergencies in differentiation and to maintain their individuality of form as far as explored.

[8] Whitman, A. R., "Rocks of the Porcupine District," Trans. Can. Min. Inst., 1916.

Contact Phenomena of the Keewatin.—Intrusion intensified the alteration started by dynamic metamorphism. The walls of the porphyry were under considerable pressure on the north and south and the basalts, for a short, distance from the contacts, were rendered highly schistose. Sometimes this contact aureole shades off into less schistose basalts, and sometimes it ends abruptly against massive basalt, being confined to a definite area between the contact and a preëxisting line of weakness. Apparently there was less stress at the ends of the porphyry where the basalts are still massive though highly carbonated. Under special conditions, where two stocks overlap, the basalts are more schistose beyond the ends. This condition is illustrated on the Hollinger 200 ft. level near No. 9 Shaft and on the lower levels east of this area.

The chemical changes do not indicate great heat. The principal change is the increase in carbonates. Sometimes the contact rock is so completely carbonated as to imitate marble. Considerable sericite is developed in the schistose types. Within 10 to 15 ft. of the contact there is a decided increase in silica. Pyrite is always conspicuous in the altered rocks in well-formed crystals, associated with chlorite and quartz. The latter is smooth and clear and entirely different from vein quartz. Generally the basalts altered to a pale buff color. At one end of the series is a gray massive carbonate rock (gray schist) and at the other end a light cream-colored sericitic schist, with all gradations between. The silicates of high temperature are conspicuously absent. Another type of alteration occurs in lenticular areas along the contact and often extends into the porphyry. Here the rocks are changed to black, glistening, sericitic schists. In thin section the rock is similar to the paler sericitic schists except that the mica is more pleochroic and is associated with carbonaceous material. The rock is apparently unfavorable to ore deposition.

Metamorphism of the Porphyry.—The Pearl Lake porphyry is highly schistose and greatly altered. At first this was supposed to be due to regional pressure acting on the porphyry after solid-

ification, but certain facts cast some doubt on this idea. Examination of a number of thin sections shows that the quartz phenocrysts are rarely fractured. There is a strong development of sericite and chlorite in the groundmass, but small unaltered areas of groundmass do not show the effects of stress. It seems more likely that the parallel arrangement of secondary minerals was assumed at the time of solidification; that the conditions favorable to the development of these minerals existed in the molten stock; and that the porphyry solidified in a gneissic condition. This is analogous to the formation of some gneisses.[8] The ease of penetration into the basalts in the east-west direction relative to the resistance to intrusion in the north-south direction, together with the hydrostatic pressure in the molten stock, is sufficient to account for the parallel arrangement of minerals at the time of solidification. Those stocks which were rich in water, and therefore capable of retaining their liquid condition at low temperatures and favoring the development of sericite and chlorite, when in the plastic state, are now found to be schistose.

ORE DEPOSITS.

Fracturing and Vein Systems.—The fractures, which are now represented by veins, seem to have been the result of readjustments following the solidification of the porphyry, for many veins can be traced from the basic schists into the porphyry. There are two general loci of fractures. Many small fractures were formed beyond the ends of the porphyry, and especially between two porphyry masses in close proximity, such as those found in the area between the west end of the Pearl Lake porphyry and the smaller stock to the south. The area of fracturing maintains its position relative to the two porphyry stocks as they recede eastward on the lower levels. Similar local fractures were formed parallel to the north and south walls of the porphyry stocks, such as the No. 4 series and the "Contact" series on the McIntyre. Such fractures when mineralized take the form of short lenticular ore-bodies, often *en echelon,* the gen-

[8a] "Fundamental Principles of Petrology," Weinschenck, page 176.

eral rule being that each succeeding ore-body is displaced to the left along the strike and into the footwall on the dip. Other fractures, however, seem to have followed more extensive lines of weakness, which can be traced from the basic schists through the porphyry and into the basic schists again. They lie in the broad zone of structural weakness already described as traversing Pearl Lake. These fractures in proximity to the porphyry contain long continuous veins. Nos. 5, 7 and 9 veins of the McIntyre belong to this class. No. 5 vein on the 1,125 level can be traced continuously for 1,400 ft. without a break, except one due to post-ore faulting. No. 7 on the 1,875 level can be traced continuously for 1,100 ft. Small parts are too narrow to be profitably mined but the continuity and regular strike of the veins are apparent. An examination of these fractures in plan and dip shows that the productive parts are confined to the tops of lava flows. The flow tops are structural lines of weakness. They tended to localize the stresses along narrow lines, giving rise to parallel systems of veins. Some idea of the importance of these major veins can be obtained from the following table:

Vein.	Production.		Reserves.	
	Tons.	Dollars.	Tons.	Dollars.
5 McIntyre.....	896,509	9,915,238	261,098	2,874,942
7 McIntyre.....	65,078	521,935	552,767	5,927,574 Partly devel.
84 Hollinger.....	693,261	10,648,683	307,359	5,303,666
53 Hollinger.....	557,173	4,478,436	284,316	2,478,112 Partly devel.

Several other of the Hollinger veins are in the same class.

With the exception of No. 5 vein, the major veins were in the porphyry on the upper levels of the McIntyre Mine. They consisted of erratic lenses of barren quartz distributed along the lines of fracturing. Owing to the eastward pitch of the porphyry they lie in the basic schists at lower elevations. The first vein south of No. 5, (No. 7 vein) emerged from the porphyry at the 1,300-foot elevation and has been productive below that.

Although the larger veins occupy lines of weakness dependent

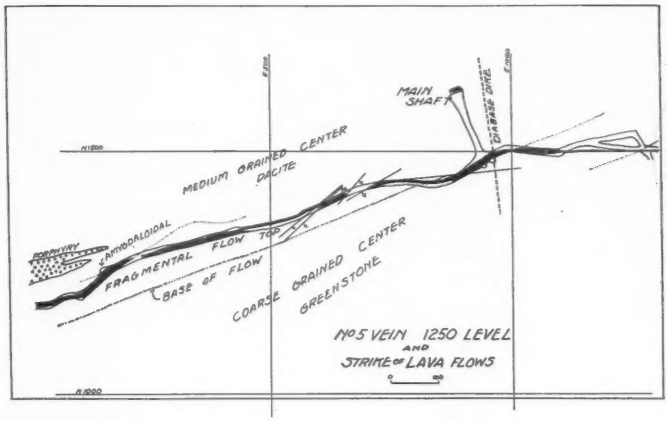

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FIG. 106. Plan of No. 5 Vein, 1,250 level, McIntyre.

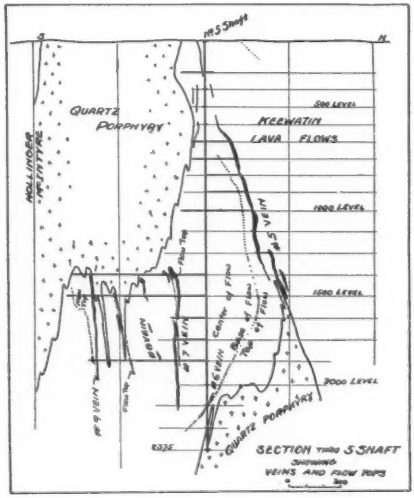

FIG. 107. Section through No. 5 Shaft, McIntyre Mine.

on structure of regional magnitude, antedating the intrusion of the porphyry, the fractures were the result of more local stress. No single vein is continuous for more than 1,500 ft. The ends of the veins die out in narrow quartz veinlets or in poorly mineralized bands of schist. Another lense may occur along the strike, usually slightly to the left. The location of the more productive parts points to the porphyry as the agent of fracturing, hence the important generalization that porphyry is essential to ore.

Vein Formation.—The mineralization of the fractures and their schistose and brecciated wall rocks followed closely on the solidification of the porphyry. The coarsely crystalline pegmatitic character of the quartz suggests that the time interval between intrusion and first vein filling was short. The slight difference in mineralogical character of veins spacially associated with the several stocks suggests that the vein solutions were the end phases of differentiation of the individual stocks. For instance, pyrrhotite is common at the Dome mine and rare in the Pearl Lake Area. Such channels as afforded the easiest circulation were filled with coarsely crystalline quartz, the siliceous differentiate of the porphyry. The quartz is commonly associated with vein chlorite and albite and locally with tourmaline, epidote and sillimanite. In thin section it is seen to be full of gas cavities, often containing a tiny bubble of liquid showing the Brownian movement. It is identical with the quartz phenocrysts in the porphyry. The existence of gas cavities points to the filling of open fractures or at least fractures under less compressive stress than the hydrostatic head of the invading solutions. The veins often have an edging of carbonates, and towards their ends carbonates largely replace the quartz. No unusual silicates occur in the contacts, but the basic rocks are slightly bleached, impregnated with quartz and for an inch or so from the vein intensely schisted. The alteration of the wall rocks has not been analysed in detail, but evidently it differs from the contact phenomena produced by the porphyry only in degree. The texture, associated minerals, location and contact reactions of the quartz veins all point conclusively to an igneous origin. The siliceous solutions

were not auriferous, for gold is never found within unfractured quartz.

After deposition of the quartz there was additional stress, opening the veins where conditions were favorable and extending them. The quartz was crushed or at least granulated along its crystal boundaries. The solutions assumed a basic character. Pyrite invaded the refractured vein channels and the schistose wall rocks. It was most energetically deposited on the contacts between the quartz and the schists and in the schists. It is commonly associated with chlorite. A large amount of pyrite also occurs in the basalts and the porphyry near their contacts, and in fact wherever the rocks have been fractured in proximity to the porphyry the fractures have been mineralized. This contact mineralization is not appreciably auriferous, that is to say that, though ordinary methods of assay often give low gold values, gold has not been observed during the examination of a large number of thin sections and polished chips. Most of the pyrite of the ore-bodies is, apparently, of the same non-auriferous type, though in hand specimens it is usually distinguished by the greater intensity of mineralization. Some of the pyrite, however, is itself gold bearing. Polished chips show flakes of gold in pyrite which has not been cracked. Towards the end of the deposition of pyrite the veins were again fractured. This fracturing seems to have been confined to the veins, as the pyrite of the contact zones is in good crystal form. The greater part of the gold was introduced after this period and was deposited in cracks in the pyrite and quartz. The probable order of deposition seems to have been pyrite, auriferous pyrite, gold.

Sphalerite, galena, and chalcopyrite are occasional accessory sulphides. The sphalerite sometimes contains inclusions of chalcopyrite, a form of intergrowth common to sphalerite deposited by ascending solutions of igneous origin. Galena is intergrown with sphalerite. Chalcopyrite also occurs independent of sphalerite. Pyrrhotite is rare in the Pearl Lake area. Arsenopyrite occurs in some of the Hollinger veins. Altaite intergrown with galena has been noted at the Hollinger mine in one specimen. Scheelite is occasionally found.

In general there are two types of ore, siliceous ore and sulphide ore. The straight quartz ore is rather low grade with occasional coarse gold. It is increasingly rich as inclusions of pyritiferous schist are found, so that banded quartz and schist may assay well above the mill average. The sulphide ore is higher grade. The best values occur in highly mineralized dark chloritic schist carrying over 15 per cent. pyrite. Coarse visible gold is rare in the sulphide ore bodies.

Post-Ore Faulting.—The period of vein formation was followed by faulting—most evident in the upper parts of the veins. All are thrust faults, usually with small throws and limited surfaces of dislocation. The direction of movement, as shown by striations, is upward to the left to the observer facing the hanging wall. The phenomena of drag ore and step faulting is common and simplifies the problem of finding faulted sections of ore bodies. Faults associated with amorphous carbon have been encountered in all of the older mines of the Pearl Lake area. The occurrence is of great scientific interest and, owing to the fact

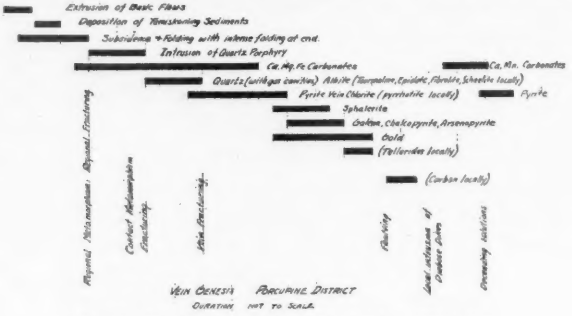

FIG. 108. Vein genesis, Porcupine District.

that the carbon precipitates gold from solutions of potassium aurocyanide, of some economic importance.[9] A number of "graphitic" faults were encountered cutting No. 5 vein of the McIntyre. The intersections with the vein form a zone pitch-

[9] Andre Dorfman, "On the Metallurgy of Carbonaceous Ores," Can. Inst. Min. and Met., March, 1922, p. 383.

ing to the east about 30 degrees. The faults are clearly post-mineral. Ore continues below the fault zone of the same character and grade as that mined above. Considerable drag ore was developed in the fault zone, which has been reserved for special treatment on account of its contamination with the highly carbonaceous wall rocks. The carbon, if present at the time of

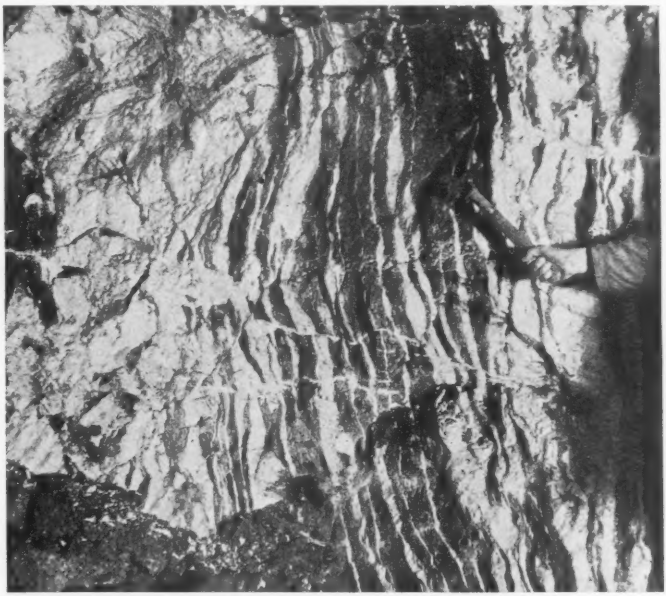

FIG. 109. Banded schist and quartz, No. 7 vein McIntyre.

precipitation of the gold, which is improbable, had no effect on the solutions. No carbonaceous sediments occur in the vicinity, but the vein lies in the tuffaceous top of a dacitic flow. Carbon occurs as a fine dust in the interstices of the coarser fragments of the tuff, and as dense flaky aggregates wherever there has been movement. There is a strong concentration of carbon in the faults, selected specimens running as high as 7 per cent. carbon.

The occurrence of veinlets of carbon in the flow top and in a small dike of porphyry nearby suggests some sort of vein filling.

Carbonaceous slates of the Larder Lake District, often amygdaloidal and interbedded with basalt flows, have been described by Dr. H. C. Cooke.[10] He concludes that the slates are partly tuffaceous. The flow top at the McIntyre presents some analogies and it is possible that such was the original source of the carbon. The principal difficulty to this theory is that the flow top is carbonaceous for only a short distance along its strike. According to H. S. Spence[11] some vein graphite is genetically related to igneous intrusion. The carbon is supposed to have been reduced from cyanogen compounds, carbon dioxide or carbon monoxide, representing the final exhalations of the magma. Some such pneumatolitic action might have introduced carbon into the brecciated zone intersecting No. 5 vein.

Influence of the Wall Rocks.—No important ore bodies occur in the porphyry. Apparently this is due to its physical condition as well as its chemical composition. The soft schistose rock did not lend itself to fracturing. At best it only opened enough to allow short erratic lenses of quartz to be formed. The secondary fracturing of the quartz, which preceeded the introduction of gold-bearing solutions, is almost entirely lacking, owing probably to the fact that the soft walls of the quartz veins would not transmit the stress to the veins themselves. The deficiency of ferrous iron minerals may account for the reduced precipitating power of the rock, where other conditions are favorable. The highly altered contact phases of the basalts are unfavorable, though many good ore-bodies occur where the quartz and schists are well banded, the values being concentrated on the quartz schist contacts. Veins in highly carbonated massive basalts are branching and irregular with low values in the wall rocks. The less altered but slightly schistose basalts contain the important

[10] H. C. Cooke, "Kenogami, Round and Larder Lake Areas," Geol. Surv. Can., Memoir 131, p. 28.

[11] H. S. Spence, "Graphite," Can. Dept. of Mines, 1919, p. 10.

ore bodies. Providing there is some schistosity it does not seem to make much difference whether the wall rocks contain little or abundant carbonates, but the dark chloritic schists are usually associated with the richest ore.

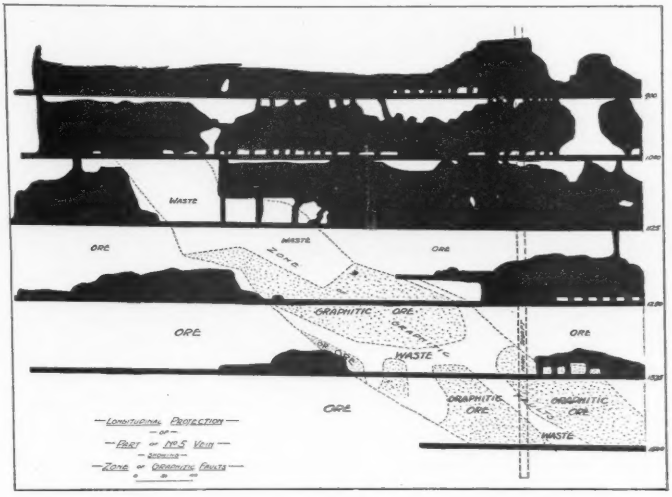

FIG. 110. Long. Section of No. 5 Vein Graphitic Zone.

Favorable Structures.—The favorable structures are:

1. Regional lines of weakness, such as the bedding planes of the flows, which served as loci of readjustment for stresses induced by the intrusion of large porphyry stocks.

2. Localized areas of intense fracturing near masses of porphyry, at the ends of such masses and especially between masses intruded in close proximity.

The great productivity of the Hollinger claims southwest of the McIntyre claim is due to the fact that the regional fractures are found there in conjunction with the localized area of intense fracturing. The overhanging porphyry and its envelope of altered rocks seems to have exerted a favorable influence, acting as

a dam to the ascending solutions. Minor joints and faults served the same purpose and often mark the upper limits of large ore bodies.

Influence of Depth.—Gold lode deposits of the Porcupine type have been found to be persistent to great depths, but rarely vertically below their outcrops, owing to the complex structure of the ancient formations. The mineralogical and structural characteristics correspond to the class of deposits formed at intermediate depths and under thermal conditions intermediate between surface deposits and high temperature deposits (Lindgren's classification). The Porcupine type approaches the high temperature type in some cases, as shown by the presence of pyrrhotite, tourmaline, and scheelite. The vertical range of the intermediate type is estimated to be from 3,000 to 12,000 feet below the original surface. For instance Lindgren states that the lowest explored Bendigo saddle reef was formed at least 7,000 feet below the surface and that the ores of the Mother Lode, California, were precipitated at 6,000 feet. The auriferous pyrite of Porcupine probably had a similar range. Just how much the original surface has been lowered by erosion is not known, but it is doubtful if the total erosion has cut down much below the upper limits of vein formation. Ore is being mined from the 2,125-foot level of the McIntyre mine and diamond drilling has encountered ore at lower horizons. There is no appreciable change in the mineralogical composition or gold content at the greatest depths. The trend of economic areas is eastward with the trend of geologic structure and this fact must be taken into account in any estimate of the future of the district. In Maclaren's words, "The non-persistence of ore with depth is a function of geological structure and not of depth." There does not seem to be any reason to doubt that ore bodies equal in size and grade to those now exploited will be found at the limits of profitable mining, providing that the peculiarities of structure are recognized, as they now are, and exploration guided accordingly.

A realization of the genetic relationship between the porphyry

and ore has stimulated exploration throughout the camp. There is a strong possibility that small porphyry masses out-cropping to the east of the productive area represent the apexes of larger stocks and that vein systems may be found at depth at the intersection of the regional zone of schisting with these stocks.

McIntyre-Porcupine Mines Ltd.,
Schumacher, Ont.

EDITORIAL

ON VEINS FROM INTRUSIVE MAGMAS WITH CONTRASTED CONTENTS OF METALS.

ALL geologists of extended experience in mining districts must have been impressed with the fact that some yield practically but one metal; as is the case in the Mother Lode gold district of California, and the Bisbee copper mines of Arizona: while others produce two or more; as at Butte, Mont., the Coeur d'Alenes, Idaho, and Leadville, Colorado. While we speak of one metal in the first instances, involving gold and copper respectively, yet iron in pyrites is also always in evidence, although of no commercial value, except, perhaps, as a help in slag formation. Rarely indeed does one metal appear entirely by itself, but one metal may be the sole object of mining. We may have a district such as southeast Missouri, wherein lead is the overwhelming product, but where also there is subordinate iron in pyrite and marcasite, usually fringing the lead-ore bodies and carrying a little cobalt and nickel. The last two with some copper and free from lead may even impregnate a lower-lying sandstone, as at Mine la Motte. The Coeur d'Alenes give us predominant lead-silver ore, but in the siderite gangue is a large amount of iron; and in some properties zinc and even copper are important. Leadville, Colorado was, as we all know, originally a gold-placer camp; then a silver-lead producer, until zinc and also copper attracted serious attention. Through all its career as a deep-mining camp, iron and manganese have been prominent associates of the lead, silver and less abundant metals.

To these several instances we may add one other case and that is a possible district of abundant vein formation, with only barren quartz. The portions of the state of Connecticut near Long Island Sound, and the parts of Rhode Island on the west side of

Narragansett Bay, do not lack quartz veins. In fact the largest quartz vein in the writer's experience or reading is at Lantern Hill, Mystic, Conn., but the most that these veins ever yield is a trace of gold.

If now, we admit once for all, that pyrite is well-nigh universal in metal-bearing veins, and is persistent in its formation over a wide range of physical conditions; and if we regard the great majority of ore-bearing veins as deposited in connection with the expiring stages of intrusive magmas, we may raise the following questions. Are certain magmas provided with no metals other than the universal iron. Do others only contain one other, and this metal usually gold. Are still others supplied with two, three or more. Or, have we cases in which there is or has been zonal distribution of metals, vertically or horizontally, but in which mining developments have only exposed a portion of the zones; or in which erosion has removed all but the lower ones. Are we justified, then in anticipating changes of metal contents in depth.

For the Mother Lode district, now that such great depth has been attained, it seems improbable that the gold-quartz veins will change. They must either belong to the zone next the pegmatites, in the series outlined by J. E. Spurr, or else the grano-diorite, to whose intrusion we naturally ascribe the veins, was provided only with gold; and that, aside from iron, we have a one metal magma. The latter view appeals to the writer as the more probable. In describing the veins in this way, the writer is well aware that relatively small amounts of galena, zinc blende, chalcopyrite, arsenopyrite and perhaps other sulphides are associated with the gold, but no one of the metals other than gold has commercial value.

By way of contrast we may well infer that the intrusive mass which caused the ore-deposition at Leadville, must have been richly stored with iron and manganese; with lead and zinc; with silver and gold and with copper.

As a supplement, therefore, to the editorial on the " Zonal Distribution of Ores around Igneous Centers " in ECONOMIC GEOLOGY for November, 1921, p. 474, and the subsequent note in the

following number, p. 46, we may add that there are some districts in which the variety of metals, necessary to the formation of zones, seems to fail; while in others the number is sufficient to make zonal precipitation possible. This supplementary note is made rather with a growing conviction of the importance of the zonal relationship, than with a diminishing one. In districts where the ore-solutions were complex and were provided with the several metals, the conception of the zonal distribution may be one of the most important working hypotheses, which those in charge of development can have. But in other camps, of veins with only one or two metals, we may be dealing with the effects of a simple magma, and may very well be cautious in inferences based on zonal distribution.

JAMES F. KEMP.

DISCUSSION AND INFORMAL COMMUNICATIONS

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NOTE ON THE DETERMINATION OF ANISOTROPISM IN METALLIC MINERALS.[1]

Sir:—The purpose of this note is to call attention to a simple method of detecting anisotropism in polished sections of opaque minerals by the use of reflected polarized light.

The effects of reflection of polarized light by polished sections of non-transparent substances have long been known. A discussion of the phenomena may be found in the various treatises on physical optics. Wright has recently summarized the effects, using, however, a mathematical method of presentation. The most useful statement of the qualitative effects is that by Von M. Berek contributed to "Anleitung zur mikroscopischen Bestimmung und Untersuchtung von Erzen und Aufbereitungsprodukten besonders im auffallenden Licht," by H. Schneiderhöhn.[2]

Up to the present time little, if any, use has been made of the methods that Wright suggested for the determination of anisotropism. One of these seems to be of particular use, namely, the measurement of the amount of rotation of the plane of polarization.

When an anisotropic metallic mineral is rotated under crossed nicols there are four bright positions and four positions at which extinction takes place. (Under certain conditions the extinction is not complete and the mineral may show faint color. The color, however, is not an interference color.) Isotropic minerals are dark during a complete revolution. Incident plane polarized light is still wholly plane polarized after reflection from an isotropic mineral and practically so from most anisotropic minerals. The

[1] Published by permission of the Acting Director of the U. S. Geological Survey.

[2] See review in this journal, no. 6, September, 1923.

brightenings seen by rotating an anisotropic mineral under crossed nicols are due to a rotation of the plane of polarization. The mineral appears bright because the analyser at 90° to the polarizer is not in position to extinguish. Extinction may be made complete by rotating the analyser to correspond to the rotation of the plane of polarization caused by the mineral. The magnitude of the effect depends both on the indices of refraction and indices of absorption.

A specimen of well crystallized manganite was investigated quantitively to determine the nature of the effects produced when an anisotropic mineral is rotated under crossed nicols. This mineral shows strong anisotropism and takes such a good polish as to cause a minimum of disturbing effects. Several of the strongest acting random sections in an aggregate were studied. The following conclusions seem justified: (1) The positions of complete extinction under crossed nicols are not always 90° apart and the divergence from 90° seems to be greater as the power of the section to rotate the plane of polarization increases; (2) The positions of greatest brightness under crossed nicols (positions of greatest rotation of the plane of polarization) may also not be 90° apart. They lie almost, or possibly precisely, midway between the dark positions; (3) The amount of rotation in alternate bright positions is opposite in direction and probably different in amount. In opposite positions the amount and direction of the rotation is the same.

The obserations on which the above statements are made were all repeated. In one case all measurements were repeated 20 times. In this case the probable errors of the mean of each series were computed by Dr. C. E. Van Orstrand and also the error which, with a probability of 100 to 1, the mean does not exceed. The results above stated are in accord with this mathematical analysis as to the accuracy of the observations.

The explanation of these phenomena must be based on a mathematical analysis which at the present time has not been carried out.

The measurement of the rotation of the plane of polarization

was measured by the method suggested by Wright using the Wright biquartz-wedge-plate. The results indicate a maximum rotative effect of at least 5°.0 with a probable error of 0°.10 or 6′.0. The apparatus used for measuring this was crude and with a good polarizing attachment such that the probable error of the zero setting could be eliminated the probable error would have been less. Although the observed angles are small, the ease and degree of accuracy with which they can be measured are such that, if there are present a few random grains of the mineral, we should at least be able to say whether the power of rotation is relatively high, low, or moderate. This is a diagnostic feature not to be overlooked, particularly as it can be applied to very small grains. Even if quantitative measurements are not to be made the ease with which we may determine anisotropism may be greatly increased by the use of the Wright biquartz-wedge-plate. If this attachment is not used, anisotropism in a fine-grained aggregate is much more apparent if the nicols are not quite at 90°, thus adding to the brightness of one grain and detracting from that of a neighbor which rotates in an opposite direction. Thus a rotation of ½° in each grain is readily apparent without even the use of a biquartz wedge.

In conclusion, I wish merely to call attention to possibilities of polarized light as a method of investigating the metallic minerals and to the use that has been made of it by Schneiderhöhn.

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U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.

METALLOGENETIC ZONES.

Sir: The conclusions of R. H. Rastall in ECONOMIC GEOLOGY, March, 1923, in regard to metallogenetic zones are very interesting. The succession in Cornwall is particularly striking. However, the veins of the Erzgebirge in Saxony and Bohemia have the same character as those in Cornwall; exactly the same metallogenetic zones can be shown in the Erzgebirge. I have previously mentioned this mineral succession in Cornwall and

the Erzgebirge [1] and proved that the uranium ore and later the sulpharsenides nickel and cobalt are intercalated between the tin-copper ores and the lead-zinc ores. I am also of the opinion that the occurrence of pitchblende in Gilpin Co., Colorado, follows this rule. By a study of the mines on Quartz Hill in the Central City Quadrangle I could prove that the pitchblende is older than the gold-bearing pyrite. If repeated, it would be clearly seen that the gold-bearing pyrite represented a gangue formation which the pitchblende cut through. On the contrary, the pitchblende is intimately intergrown with galena of an older gangue formation, which agrees with the conclusions of Spurr. The statement given by Bastin somewhat later is divergent and I cannot agree with it. In Cornwall and the Erzgebirge, however, it is perfectly clear that the pitchblende was intruded between stages 7 and 8 of Rastall.

W. PETRASCHECK.

LEOBEN, AUSTRIA.

[1] *Verhandlungen der k. k. geologischen Reichsanstalt*, 1915, p. 52.

REVIEWS

The Ore Magmas. By JOSIAH EDWARD SPURR. Two volumes, 915 pages. McGraw-Hill Book Company. Price $8.

The Author's geological studies have extended over thirty years of the most productive period in the development of the science of ore deposits. In the earlier years as a member of the U. S. Geological Survey and later in studies for mining companies he has had an unusually broad field experience.

This work presents a large body of facts collected during that period, some of which have been elsewhere recorded but many of which are made available for the first time in this book.

From Mr. Spurr's earlier writings all will expect in this volume a vigorous exposition of the theory of the magmatic origin of ores and in this they will not be disappointed. The whole work is built around this central theme of which the author was an early and has been a consistent and persistent advocate.

An idea that the author advances and especially emphasizes is that of the high concentration of the constituents of an ore in the solution or "ore magma" from which it was formed. This contrasts with the idea of relatively low concentration which is held by many and formerly was held by the author.

The reader should not overlook the author's statement that this is a series of essays setting forth his personal views. It is not a text book as it leaves numerous features but scantily touched and makes no pretense at presenting the generally accepted views or alternative views. The author makes a vigorous presentation of his views but usually largely or entirely ignores opposing ideas. Such a presentation is effective in getting the author's ideas to the reader, but of course does not give and is not intended to give a general idea of the thought and opinion of geologists on the subject.

The work might really be regarded as a scientific autobiography. We are familiar with such writings for statesmen, educators, business men, and other types of workers, in which the view of the individual and the part he has taken in his profession are emphasized. In economic geology we have had little of such writing but it would seem that there is a place for it.

It is entirely impracticable to bring out in a review of this character

the wealth of observation and deduction contained in the volumes. They must be read and studied. The following paragraphs will, however, give some of the principal features of the book.

Magmatic Differentiation.—In the opening chapter the author discusses magmatic differentiation as a fact but only briefly the theories as to how it is accomplished. It is concluded that both acid and basic rocks are derived from a magma of intermediate composition. The acid differentiates are especially considered and the views regarding them are discussed. All the acid differentiates from granite through pegmatite to pegmatitic quartz veins (vein dikes) are thought to have had a common origin and were stages in differentiation. In the pegmatites the rarer metallic elements are not abundant, tin, tungsten, molybdenum, and possibly gold being the only metals sufficiently abundant to form ores.

The following stage however, quartz veins (or vein dikes) furnishes valuable gold deposits such as those of California, Yukon, Alaska, and other districts.

From this start similar reasoning is used to extend the acid differentiate to include quartz veins, certain sulphide veins, and finally to the late Tertiary silver-gold veins, all of which are regarded as intrusive.

Fragments of wall rock suspended in veins are emphasized as proving the viscous character of the vein forming solutions.

Emplacement of Magma and Structural Results.—Examples are cited of schistosity associated with intrusions and the conclusion reached that schistosity has resulted from the slow flowage of the intruded rock to make room for the magma. While the possibility of space being made by stoping of the intruded rock is entertained, the author favors the idea of forcible displacement. The intrusive force is regarded as inherent in the magma itself rather than due to gravity or thrusts and to be due to the gas pressure of the magma. Numerous examples of domes, block fault ranges and plateaus on a small and grand scale are cited as the result of magma intrusion. In short the author attributes most of the structural features of the earth's crust to the movement of magmas.

The emplacement of the magma is separated into two periods, first, a "surgence" which raises or domes the overlying rocks, and second, a partial subsidence which has resulted in the relative depression of certain areas notably the fore deeps of the Pacific as that just off the Andean coast of South America and the "back-trough" on the east front of the Sierra Nevada and other ranges.

The magma in this region is regarded as moving continent-ward from the Pacific basin as a slow flow, to preserve isostatic adjustment but the actual intrusion is believed to result from gas pressure within the magma.

Sequence of Metal Deposition.—Examples are cited to show a regular sequence of metals upwards or outwards from a region of maximum

heat and pressure. A typical series is barren lime silicates; "cupriferous" pyrite; arsenopyrite; pyrite and pyrrhotite; zinc blend; galena; calcite. It is pointed out that in the closing stages the minerals of a later period may be superimposed on those of an earlier and that in some deposits the order may be reversed indicating deposition during rising temperature.

The Tertiary types of gold-silver veins are regarded as having formed at depths of a few hundred to a few thousand feet from the surface; they contain all the temperature types of the deeper deposits but due to rapid cooling the different zones have been compressed or "telescoped" so that they overlap and intermingle.

Two types of siliceous rocks result from differentiation, one an aplite, the other pegmatite. By analogy the author makes two types of veins, the aplite which he regards as relatively dry or free from gases and which produces little reaction with intruded rocks; and the pegmatite or "super pegmatitic" type which is rich in gases, and penetrates and reacts with invaded rocks. "Contact deposits" are regarded as formed by the latter.

Time Relation between Rock Intrusion and Ore Intrusion.—The rule is formulated that rock intrusion immediately precedes ore intrusion though exceptions are recognized.

Dikes and veins characteristically occupy fissures with little displacement while the larger faults follow the ore period. The explanation for this is that the "ore magma" enters the first openings and that the ore period is a relatively brief one. Following the ore deposition there is a long period during which adjustments to the solidifying and cooling magma cause differential movement especially in the superficial rocks.

It is the author's conception that "ore magmas" form at great depth, in the zone just above that of permanent magma, where, over great periods of time, various types of ore magmas may form and eventually rise into the overlying rocks.

While recognizing that the magma crystallizing in the higher zones must expel large quantities of water and volatile substances, the author does not believe that these form metallic deposits of commercial importance.

The formation of ore deposits has been confined to a few restricted periods. In the main these were contemporaneous with periods of igneous activity, folding and faulting, which suggests that all were associated events and that all were catastrophic rather than uniformitarian.

Distribution of Metals.—In a broad way the several epochs of ore formation are characterized by certain metals, the younger representing those formed near the surface, and the older those that have been exposed by deep erosion. The author points out that in Arizona all the

epochs are characterized by copper, making this a distinct metallogenic province. Also tin, tungsten, vanadium and others are very restricted in their occurrence.

The author conceives of the outer portion of the earth as consisting of three zones: (1) an outer consolidated zone; (2) an intermediate magma zone; (3) a lower zone, rich in metals, that has undergone a high degree of differentiation and is therefore heterogeneous.

The intermediate zone consists of two parts, the upper is the zone of crystallization and differentiation, the lower the zone of flow. The magma moves from the regions below the ocean basins to those below the continents in the lower portion of the intermediate zone (2). It gets its charge of metals from contact with the lower zone (3) and differentiates into rock and ore magmas in the upper part of the intermediate zone (2).

Metallogenic provinces are regarded as primarily due to the heterogeneous character of the lower zone (3). In addition to the Arizona copper province a great silver belt along the west coast of North and South America is pointed out together with smaller belts in Colorado, Utah, and elsewhere. These belts do not conform to geological structure, in fact they cut across the structure and are regarded as being related to the deep zone below the influence of surface structures.

Ore Depositing Solutions Other Than Magmas.—The author shows that many of the more abundant minerals are formed by surface waters, as limestone and salt deposits; others are formed by the leaching of certain elements and the concentration of others as kaolin deposits.

The great importance of surface waters in reworking metallic deposits as in the process of secondary enrichment of deposits of copper and silver is recognized. It is concluded, however, that all the primary deposits of the rarer elements have come from magmatic sources and that only the more abundant elements have been concentrated by surface waters.

Relation of Metals to Types of Rock.—Certain minerals are closely related genetically with certain kinds of igneous rock. Thus chromite and platinum are associated with basic rocks while tin and molybdenum are associated with siliceous rocks. Certain other metals as copper, lead, and zinc are associated with both types but the nature of the accompanying gangue minerals gives an indication of the source. The basic derived ores contain relatively little silica as compared with those derived from the siliceous magma and they are also relatively low in sulphur.

Three main lines of descent of ore magma are postulated: basic, intermediate and siliceous. The basic is characterized by chromium and nickel as its high temperature deposits; the intermediate by gold; and the siliceous by tin and tungsten. Copper, lead, zinc, and silver are common to all in the lower temperatures.

Metamorphosing Solutions and Causes of Precipitation.—It is postulated that lime silicates will form if siliceous solutions enter limestone at the proper temperature or if calcareous solutions enter siliceous rock at similar temperature. Thus the lime silicates may be abundant in the limestone or in the intrusive rock depending on the character of the solutions. Calcareous solutions are thought to produce only recrystallization in limestone but to form silicates in intrusive rock or in shale. Calcareous solutions may be original from a basic magma or result from the reaction of originally siliceous solutions with limestone.

The reaction of unlike substances is also necessary for precipitation of ore minerals. Thus solutions derived from siliceous rocks precipitate by reaction with calcareous rocks while the reverse is thought to hold for calcareous solutions. Hydrocarbon and carbon compounds are regarded as precipitants of certain minerals. The mingling of different types of magmatic solutions is regarded as an important cause for ore shoots.

Origin of Fissure Veins.—It is assumed that rock and ore magmas are in a state of gaseous tension that furnishes intrusive force. The veins or dikes, however, commonly occupy fissures or faults. Such fissures or faults are regarded as of two main types, (1) intrusion faulting which is the result of pressure of a rising magma, (2) adjustment faulting which follows the solidification and shrinkage of the magma and accompanies gravitational adjustment of the rocks.

The lenticular character of veins in schist is attributed to the closing in of the walls of the veins after the vein material has partly consolidated and lost its gas pressure.

(This would seem to imply in some veins a very considerable loss of volume and consequently a rather aqueous or gaseous filling.)

Sequence of Gangue Minerals.—Earthy vein or gangue minerals as well as the metallic minerals follow a definite sequence. The carbonates form most abundantly following the sulphide stage; first mixed iron-magnesium-calcium carbonate followed by calcite. The material for both these stages is regarded as injected as gelatinous substance which consolidated quickly. It included and supported fragments of rock or earlier vein. Quartz has a wider range as does fluorite. Barite is regarded as generally late. It is pointed out that iron is present in three stages but in different combination in each. At the higher temperature it forms as silicates and oxides; in the main ore stage as sulphides; and in the post ore stage as carbonate.

"Sand breccia dikes" are regarded as magmatic "vein dikes" in which the fragments are carried in a magma solution.

Certain breccia filled ore chimneys are ascribed to the action of gas advancing before an ore magma. The rock is brecciated and the fragments partly rounded by the advancing gas which in turn may be followed by ore magma which cements the broken rock.

It is obviously not practicable to comment on the divergence from current views on all the subjects treated.

The author will find a large following in many of his views and observation will be stimulated as regards others.

In the chapter on differentiation the reader does not get the clear-cut conception of the process involved that he does of the fractional crystallization idea as presented by Bowen for instance, or of assimilation as discussed by Daly. One would like to have the "ore magma" discussed from the chemical view point as Bowen has treated rock magma crystallization and the reaction with inclusions and walls. This of course is a job for the chemist guided by the experience of the field geologist.

In considering veins as intrusions of a viscous substance that has opened and filled fissures, many will follow the author through the pegmatites and possibly to the pegmatitic quartz veins who will hesitate when they come to the sulphide deposits. This hesitation will not be lessened on learning that a type example, the Mandy ore body of Schist Lake, Manitoba, is regarded by two other geologists as a replacement deposit and closely related neighboring deposits are regarded by the author and the other geologists as replacements.

Fragments of wall rock suspended in the veins are emphasized as proving the viscous character of the ore-forming solutions.

Such fragments have puzzled many of us and if the viscous character of the solutions proves to be the answer, it will be welcome.

It has been shown by Lindgren and Loughlin that the early mineralization in the Tintic district was the complete replacement of bodies of limestone and dolomite by gelatinous silica which later crystallized into chalcedony and quartz. Some squeezing and movement of such material might well give the appearance of flow and even intrusion to a body that was deposited as a replacement. There is certainly room for consideration of a similar process in the formation of the cherty quartz that frequently replaces carbonates in the Tertiary gold-silver veins.

Inclusions in many veins as well as the wall rocks have been greatly changed in composition during mineralization yet the vein material frequently contains little of the material that has been removed. We have been accustomed to think of this material as passing on with the solutions. If such veins formed in a manner similar to dikes, should we not expect the material lost from the walls to appear in the veins?

The sharp change in the metal content of a vein that sometimes occurs where it passes from one rock to another does not seem consistent with the idea of intrusion as a viscous magma that filled the space the vein now occupies and solidified to make the vein. It seems more consistent with formation from a solution flowing through the vein that reacted differently with different rocks.

As regards gas pressure as the main intrusive force; the high gas pressures that develop in magmas on crystallization have been indicated by the experiments of Morey, and this source of pressure has been used to explain volcanic outbursts by A. L. Day, so that for the crystallizing stage of magmas at least there seems good experimental evidence for the belief that such pressures exist and may be maintained during crystallization even into the vein stage, as has been suggested by Graton.

It may be worth noting, however, that if the geologists who believe in the intrusive emplacement of the salt in salt domes are correct, gravity is probably capable of producing intrusion without the aid of an internal force and may well be a large factor or a main factor in magma intrusion. The author, however, does not accept gravity as the cause of salt dome intrusion.

The structures attributed by the author to magma "surgence" and a later partial subsidence remind one of LeConte's explanation of basin range structures by a doming of the rocks and a subsequent collapse of the dome, an idea that, with modifications, has been followed by several later writers. The importance of such subsidence faults will be recognized by most field geologists.

The "telescoping" idea (Chapter 6) to explain the Tertiary type of gold-silver veins will doubtless meet with objections. The reason for the failure of many of the Tertiary gold-silver veins at relatively shallow depth is one of the problems of ore deposits that has not received a very convincing and satisfying answer.

The author fully recognizes the difficulties of the problem but the reader is led to infer (Chapter 6) that the shallow depth is due to the fact that high temperatures prevailed very close to the surface with a rapid gradient to low temperatures at the surface so that the whole range of mineralogical types from tungsten and tin to silver was compressed or "telescoped" into a few hundred or few thousand feet. Below this the temperature was above that favorable to ore deposition. Later (Chapter 16) many of the deposits are ascribed to rising temperatures that superimposed higher temperature deposits on lower but this fails to account convincingly for the sudden failure of so many of these deposits at depth.

There are certain characteristics of these Tertiary veins that are not found in the deeper veins. In many if not most of the Tertiary veins, quartz and adularia have replaced earlier carbonate veins. This would seem to furnish conditions similar to those resulting in lime and lime iron silicates in the deeper zones yet except for adularia silicates are rare. Magnetite, hematite, and all the ferric minerals are generally absent. Mr. Spurr notes some veins regarded as of this type in which lime-iron silicates have formed. While adularia is the common potash aluminum mineral, alunite is by no means rare in closely allied veins and in some of the metal veins, and there seems reason to suppose that the

temperature conditions for the formation of the two minerals are not very different. Alunite seems clearly a low temperature mineral, doubtless lower than adularia. The relative proportions of the rarer metals as copper, lead, zinc, gold, and silver, is usually different from that of the deeper deposits.

To the reviewer, mineral combinations seem far surer indications of temperature conditions than metals. Iron occurs through the whole range but ferric minerals in sulphide veins are pretty definitely confined to high and moderately high temperature and to surface conditions. In types formed at intermediate and low temperatures, ferric minerals are largely absent. Potash and aluminum occur through the whole range but sericite is most abundant in the high and intermediate temperatures while alunite is a low temperature mineral. The author points out that silica forms different minerals at different temperatures. He also recognized recurrence of periods for gold and silver and to some extent for other minerals. Is the evidence convincing that there is no recurrence of tungsten and tin? Many students will doubtless still feel that an entirely convincing explanation of the failure of the Tertiary veins at relatively shallow depth is still to be made.

The more hypothetical and theoretical parts of the book such as the cause for metallogenetic provinces, the migration of magmas, and the relation of magma movement to different types of structure are bound to stimulate thought and observation though some of the problems are of course beyond proof and must for the present at least remain more or less open.

In the preceding paragraphs the reviewer has emphasized some of the ideas on which there is likely to be differences of opinion. This seems justified because these are the ones on which additional evidence or confirmation is needed before they can either be placed with the great body of generally accepted fact or rejected. An idea that is clearly demonstrated, no matter how important and valuable, can be given its place with little discussion and many such will be found in this work.

Among those advocated that already have a large acceptance may be mentioned the idea that the solutions that formed many ore deposits are a differentiate of an igneous magma and are closely related to pegmatites; the zonal arrangement of metals; and in structure, the "subsidence" faults that so commonly follow igneous intrusion and ore deposition and are an important economic factor in many districts.

This book should be read by every student of ore deposits. The impression on older workers will be varied. To beginners the unity and relative simplicity of the scheme must make a strong appeal. The reviewer would recommend to the latter group the reading, as a counter irritant, of some report showing the possibilities of other theories of ore

genesis, as Siebenthal's paper on the origin of the deposits of the Joplin district.

It would be futile for the reviewer to venture an opinion as to how the new views set forth in this paper will be regarded after they have been fully considered and tried out but there is little doubt that they will stimulate observation along numerous lines and that the science will be on a solider foundation from the observations so stimuated.

The books are well printed with abundant instructive illustrations. Doubtless a search would reveal typographic errors but few were noted by the reviewer whose attention was fixed on the substance presented.

Mr. Spurr has done a very distinct service in contributing this summary of his long and varied study of ore deposits.

These volumes record numerous changes from the views held by the author at earlier periods. These earlier views have been freely discarded where later experience has shown their weakness. The author shows that he possesses not only the virtue of persistence in views that he regards as sound but also the rarer if not the greater virtue of freely discarding earlier ideas that seem to have outlived their usefulness. All who have had many ideas find some of the latter kind in their collection. The author is still, we trust, in the midst of his career and we may expect future papers with further development of the main themes and perhaps some further change of views on some of the subjects treated.

B. S. BUTLER.

CALUMET, MICHIGAN.

The Nature and Properties of Soils. By T. LYTTLETON LYON AND HARRY O. BUCKMAN. From the Agricultural Science Series, edited by L. H. BAILEY. The MacMillan Co., New York, 1922. 588 pp. with 64 figs. and 131 tables.

This is a scientific study of soils from the geological, physical and chemical points of view, but always the emphasis is laid on the practical relation of soil to plants. Various chapters treat of soil structure and composition, and the moisture, heat, air, and absorptive properties of soils. Experimental methods of testing are described, with results in tabular form. Chemical analysis of soils is briefly treated, as the writers do not believe it to be of direct practical value. There is a discussion of soil alkalinity and soil acidity, with methods of eradicating these conditions, and a study of soil organisms. Perhaps the most helpful part of the book is the section devoted to various types of fertilizers and their use. This should be of immediate value to the farmer, as all conditions and remedies are referred to specific crops, and there are many suggestions for actual farm practice.

The book is clearly and interestingly written. There is abundant reference matter and a complete bibliography and index.

A. A. BEECHER.

SOCIETY OF ECONOMIC GEOLOGISTS

Arrangements for Annual Meeting.

Committee.—President Spurr has appointed the following Committee on Arrangements for the Washington meeting: D. F. Hewett, Chairman (Address—U. S. Geological Survey, Washington, D. C.), Arthur C. Spencer, Henry G. Ferguson. On request this committee will make hotel reservations for members for the dates of the annual meeting, in association with the Geological Society of America, December 27–29, 1923.

Luncheon.—As previously announced, there will be no separate sessions of the Society at Washington, except the annual meeting, as provided by the Constitution, for the transaction of business. It is expected that arrangements will be made for holding this meeting in connection with a special luncheon, definite announcement of which will be mailed to the members.

G. S. A. Meeting.—All members are invited to attend the sessions of the Geological Society of America, to participate in the discussion of papers, and to attend the annual dinner, which will be held on Thursday evening, December 27. Members are also invited to the annual smoker tendered by the Geological Society of Washington, at the Cosmos Club, Thursday evening, December 27, at 9 o'clock.

May Meeting, 1924.

Committee on Papers.—President Spurr has appointed the following Committee on Papers for the May, 1924, meeting in New York City: George H. Ashley, Chairman (State Geologist, Harrisburg, Penn.), D. F. Hewitt, Willet G. Miller, Arthur C. Veatch, Per Geijer, E. C. Andrews, Lewis L. Fermor.

SCIENTIFIC NOTES AND NEWS

G. F. Loughlin will act as the geologist in charge of the work on metalliferous deposits during the absence of F. L. Ransome at the University of Arizona.

Sydney H. Ball has returned from Brussels.

F. H. Lahee, chief geologist of the Sun Oil Company, is at present temporarily engaged in foreign work

S. J. Schofield, of the University of British Columbia, has sailed for the Orient for a year's geological work in China.

Loftus Hills, director of the Geological Survey of Tasmania, has accepted an important position in South Africa.

Joseph T. Singewald, of the Geological Department of Johns Hopkins University, spent the summer in Mexico for the Transcontinental Petroleum Company.

J. H. Warner, who for fifteen years has been consulting engineer and geologist for the East Butte Copper Mining Company, is now chief geologist and consulting engineer of that company.

W. E. Wrather has financed new buildings for the University of Chicago field station in Missouri in addition to the ten acres of land previously donated by him.

Robert E. Dye, formerly consulting engineer of the Keeley Mine, South Lorrain, has been appointed manager of the Vipond Consolidated of Porcupine.

Douglas R. Semmes, assistant chief geologist of the Mexican Eagle Oil Company, has left Tampico to spend several months at the Hague.

R. W. Ellis, State Geologist of New Mexico, and David S. Hill, president of the State University, have prepared a report on the present status of oil and gas development in New Mexico.

Rene Engel, formerly mining engineer for the Anaconda Copper Mining Company, has resigned to accept the chair of geology at the Oklahoma School of Mines.

Ulrich Laues is with the Granada Oil Corporation, with headquarters at Baranquilla, Colombia.

H. G. Nichols, of Vancouver, has been appointed associate editor of the Canadian Mining Journal.

Fred Hall Kay is in general charge of the Sun Company's petroleum interests in Venezuela.

Holmer A. Noble is engaged in micro-paleontological work for the geological staff of the Marland Oil Company of Mexico, at Panuco, Veracruz, Mexico.

C. W. Gudgeon has resigned his position as general manager of the Mount Bischoff tin mine, Tasmania.

Paul Weaver, formerly chief geologist for the Aguila, is now in charge of the Dutch Schell geological work in the Isthmus of Tehuantepec.

P. P. Goudkoff, of the Tomsk Institute of Technology, Siberia, is also with the McKanna Syndicate as a geologist.

E. S. Perry, formerly head of the department of geology at the University of Kentucky, has accepted a similar position in the New Mexico School of Mines at Socorro, New Mexico.

W. N. Logan, State Geologist of Indiana, is in charge of the preparation and issue of a large number of reports on the geology and oil, gas, and coal resources of the state.

W. M. Rau, formerly professor of geology and mining at Acadia University, Wolfville, Nova Scotia, is now engaged in consulting work at 9 Lesher Street, Boston.

John M. Herald has resigned his position as head geologist of the Roxana Petroleum Corporation to form a partnership with his brother, Frank A. Herald, for consulting work, with headquarters at Tulsa, Oklahoma.

Spencer Hutchinson and Robert Livermore have formed a partnership as mining and consulting engineers, with offices at 201 Devonshire Street, Boston, Mass.

T. E. Swigart, Superintendent of the Petroleum Experiment Station of the Bureau of Mines at Bartlesville, Oklahoma, has been granted a furlough of some months and has gone to India for the Attock Oil Co.

John R. Reeves has finished extensive field studies in connection with the survey of the oil resources of Indiana which is being conducted by the Bureau of Mines in coöperation with Indiana University.

R. C. Tucker, of the West Virginia Geological Survey, has prepared a structural map of Ohio, Brooke, and Hancock Counties, West Virginia.

Takeo Kato writes from Japan: "My family and I have fared quite well throughout the earthquake and fire. Of our university buildings, all belonging to the colleges of law, economics and letters, and some belonging to the colleges of medicine, science, and engineering, together with the main university library containing about 700,000 books, were destroyed by fire. Fortunately, the geology building has escaped from fire, though serious damage was done by earthquake. Most books of geology and allied sciences have been put in our department library, so we can continue investigations as before.

"I wish to acknowledge that our countrymen are expressing hearty thanks to your countrymen for the sympathy with the sufferers by the disaster."

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